Pages in the development of neutrino physics

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This review is quite subjective in nature, is incomplete, and can certainly not be regarded as a chapter in the history of particle physics. It consists of a collection of several short sketches associated with neutrino physics. Two of them, concerning Pauli and Fermi, are among those which in recent years have been published fairly frequently by a number of physicists, including the present author, in connection with the recent fiftieth anniversary of the "invention" of the neutrino. The story concerning the work of Majorana on the Majorana fermions which follows has not been discussed in such detail previously, at any rate not in the pages of Soviet journals. Then follow some reminiscences of quite personal nature associated with the experimental and theoretical work of the author on the proposal and development of radiochemical methods for neutrino detection, among which is the chlorine-argon method, on the suggestion of the existence of neutrino oscillations and their use in neutrino astronomy of the sun, on the establishment of the concept of weak processes and important properties of muons, on the proposal of new type of investigations of the weak interaction, on experiments with high energy neutrinos . . . . In order to reduce to some extent the extremely subjective nature of the review, the author summarizes in Tables I–IV important events in the history of neutrino physics up to 1980, and also provides a list of the large installations for the study of neutrinos.

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CONTENTS

1. INTRODUCTION

Five years ago on the seventieth birthday of E. Amaldi I was invited to give a review paper on neutrino physics at an international conference of physicists the majority of whom were not specialists in this field. However this report was not published. In 1980 I gave a paper intended for specialists in the field of neutrino physics and astrophysics at the international conference "Neutrino 80".[1] Quite recently I gave a paper at the international colloquium on the history of elementary particle physics which took place in Paris.[2] The editors of "Uspekhi Fizicheskikh Nauk" invited me to prepare an article on the basis of the above reports. The present article is naturally quite eclectic: in it are recounted incidents and events in the history of neutrino physics well known to specialists, and also less known episodes; it deals with very old and occasionally with quite new material. The literature cited is quite incomplete and is of a fairly random nature . . . The events related are not a sequential account of the development of neutrino physics. They are only a few

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episodes from the history of neutrino physics. Moreover, I am relating only those events which have influenced me personally. Some of them are of a decisive significance in the history of neutrino physics and astrophysics, others are not so significant but are well known to me. All these episodes I "saw" either with my own eyes or with the eyes of persons who were close to me. I ask forgiveness from many physicists, among them some of my friends, for the fact that I have not devoted to them the attention which they would have a right to expect in an objective account.

Thus my account will be very subjective. It is intended both for nonspecialists and for young investigators in neutrino physics who are well informed concerning the events of today and yesterday but not so well informed concerning the ancient ones. These physicists are accustomed to thinking in terms of 10^5 or 10^6 neutrino events. They have forgotten (or they have never known) that even 16 years after the "invention" of the neutrino by Pauli it was still regarded as an undetectable particle.

Neutrino physics is almost a synonym for weak interaction physics, but there is a difference. I have not always been conscious of this difference.

In the second section of this article a list of events that have occurred in neutrino physics is presented in the form of tables. This is done, first of all, in order to diminish to some extent the subjective nature of the account. And nevertheless the tables are still not objective. They mention events which had a decisive significance or which initiated a large number of research papers. A second object of the tables is as follows: even a dry, subjective and incomplete list of events will enable the reader to enter quickly the atmosphere of those years to which this article is devoted.

At first I was compiling the tables without using the literature, simply by memory. When, finally, something had to be stated more precisely or more completely I had to spend much time, but there were few corrections to be made.

The tables refer to four periods selected more or less arbitrarily.

The first covers the period from the discovery of radioactivity to the neutrino hypothesis, the Fermi theory of β-decay and to the discovery of free neutral leptons (the incubation period and the childhood of neutrino physics).

The second covers the period from the observation of weak processes different from β-decay, up to the discovery of nonconservation of parity in weak processes, the V-A universal theory and up to the observation of the *PC* violation (adolescence of neutrino physics).

The third covers the period from the birth of high energy neutrino physics and the discovery of two types of neutrinos up to the discovery of neutral currents, the τ lepton, the processes of decay of charmed particles and the theory of electroweak interactions (maturity of neutrino physics).

The fourth deals with neutrinos in astrophysics, astronomy and cosmology. In supplementary tables IIIa, b and c some information is given concerning neutrino beams and large neutrino detectors (status up to 1980).

Already a first glance at the tables shows as the main point the tremendous growth of neutrino physics which has become a quantitative science, healthy and powerful and yet carrying the promise of qualitative unexpected discoveries.

2. A LIST OF SIGNIFICANT EVENTS. LARGE NEUTRINO INSTALLATIONS

TABLE I. *From the discovery of radioactivity to the neutrino hypothesis, the theory of β-decay and to the discovery of free neutrinos* (1896–1956).

Year	Event	Authors
1896	Discovery of radioactivity	Becquerel
1899	Discovery of β-rays	Rutherford
1908–1928	Counters (proportional and Geiger) capable of detecting individual charged particles	Geiger Rutherford Müller
1912	Wilson chamber	Wilson
1914	Continuous β-ray spectrum	Chadwick
1925	Method of thick photographic plates	Mysovskiĭ
1927	Measurement of heat liberated upon absorption of β-rays	Ellis, Wooster
1927	Quantum theory of radiation	Dirac
1928	Relativistic equation for particles with spin 1/2	Dirac
1929	Two-component theory for fermions with zero mass	Weyl
1930	"Invention" of the neutrino	Pauli
1932	Discovery of the position	Anderson
1932	Discovery of the neutron	Chadwick
1932–1933	A nucleus consists of nucleons	Ivanenko; Heisenberg; Majorana
1933	Theory of β-decay	Fermi
1934	Artificial radioactivity	Curie, Joliot
1934	β-radioactivity with emission of positrons	Curie, Joliot
1934	First discussion of inverse β-decay	Bethe, Peierls
1934	Vavilov-Cherenkov effect	Vavilov, Cherenkov
1935	Meson theory of nuclear forces	Yukawa
1935	First experiment on observing recoil nucleus in β-decay	Leipunsky
1935	First investigation of double β-decay	Goeppert-Mayer
1936	Far-reaching consequences of the fact that the Fermi constant is not dimensionless	Heisenberg

Table I cont.

Year	Event	Author
1936	Kurie plot	Kurie, Richardson, Paxton
1936	Gamow-Teller selection rules in β-decay	Gamow, Teller
1937	Majorana neutrino	Majorana
1937	Observation of capture of orbital electrons by nuclei	Alvarez
1937	First mention of weak neutral currents	Kemmer
1938	Discovery of the muon	Anderson, Neddermeyer
1939	Diffusion chamber	Lungsdorf
1939	First discussion of neutrinoless double β-decay	Furry
1939	First idea of a nonabelian intermediate boson	Klein
1942	First nuclear reactor	Fermi
1944	The principle of phase stability, several years later begins the era of experiments carried out using new types of powerful accelerators	Veksler; McMillan
1945–1959	Crystal counters and semiconductor detectors	van Heerden MacKay MacKenzie Bromley
1946	Proposal to detect low-energy neutrinos with the aid of radiochemical methods	Pontecorvo
1947	Scintillation counter	Kallmann
1948	Observation of radioactivity of the neutron	Snell; Robson Spivak
1949	First measurements of the β-spectrum of tritium	Curran *et al.*; Hanna, Pontecorvo
1950	Cherenkov counter	Jelley
1952	Bubble chamber	Glaser
1953	Concept of leptonic charge	Marx; Zel'dovich; Konopinski, Mahmoud
1953–1956	First observation of free neutrinos from a reactor	Reines, Cowan
1956	The reaction $\bar{\nu}_e + \mathrm{Cl}^{37} \rightarrow e^- + \mathrm{A}^{37}$ is not observed	Davis

TABLE II. From the observation of weak processes different from β-decay to the discovery of nonconservation of parity in weak processes, the creation of the V-A universal theory and to the discovery of *CP*-noninvariance (1941–1967)

Year	Event	Authors
1941	Direct proof of the radioactivity of the muon and the measurement of its lifetime (experiment carried out on cosmic rays)	Rasetti; Rossi, Nerenson
1947	The muon is not a hadron (experiment carried out on cosmic rays)	Conversi Pancini, Piccioni
1947	"Two-meson" theory	Marshak, Bethe
1947	Discovery of the pion and the $\pi \rightarrow \mu\nu$ decay (experiment carried out on cosmic rays)	Lattes, Occhialini, Powell
1947-	Concept of a deep analogy between the electron and the muon (universality of 4-fermion interactions) and the concept of "weak processes"	Pontecorvo; Klein; Puppi
1947	Discovery of strange particles in cosmic rays	Rochester, Butler; Leprince-Rinquet
1948	Nonexistence of the $\mu \rightarrow e\delta$ process (experiment carried out on cosmic rays)	Hincks, Pontecorvo; Sard, Althaus; Piccioni
1948	Observation of artificially produced pions. After this notable event using accelerators precise measurements of pion and muon masses and lifetimes have been and are still being carried out. Later quantitative investigations of properties of strange particles were begun using accelerators all over the world	Gardner, Lattes
1949	Three particles are emitted in μ-decay, one of which is an electron (experiment carried out on cosmic rays)	Hincks, Pontecorvo; Anderson; Steinberger; Zhdavov
1950	Parameter ρ characterizing μ–e decay	Michel
1950	Proposal of strong focusing for accelerators	Christofilos *et al.*

Table II cont.

Year	Event	Author
1952	"There remains the disturbing possibility that P and C are both approximate and PC is the only exact symmetry law"	Wick, Wightman, Wigner
1953	Hadron isotopic multiplets-strangeness	Gell-Mann; Nishijima
1954	Yang-Mills fields	Yang, Mills
1955-1956	Dual properties and oscillations of neutral kaons	Gell-Mann, Pais; Piccioni
1955	First observation of the antiproton	Chamberlain, Segre
1954	CPT theorem	Lüders; Pauli
1955–1956	$\theta-\tau$ paradox, i.e., nonconservation of parity in decays of strange particles	Whitehead *et al.*; Barkas *et al.*; Dalitz *et al.*; Harris *et al.*; Fitch *et al.*
1955	Conservation of vector weak current	Gershteĭn, Zel'dovich
1955	Principle of "triggered power supply" on which is based the operation of such track detectors as spark and streamer chambers	Conversi, Gozzini, Tyapkin
1956	Discovery of the neutral kaon with a long lifetime	Lande *et al.*
1956	Is parity conserved in weak interactions?	Lee, Yang
1957	Hypothesis of PC-invariance	Landau; Lee, Yang
1957	P and C are violated in the decay of cobalt-60	Wu *et al.*
1957	P and C are violated in π and μ decays	Garwin, Lederman, Weinrich, Telegdi
1957	First model unifying weak and electromagnetic interactions	Schwinger
1957	Two-component neutrino	Landau; Salam; Lee, Yang; Sakurai
1957	Observation of longitudinal polarization of β-particles	Frauenfelder *et al.*; Alikhanov *et al.*; Nikitin *et al.*
1957	Neutrino oscillations?	Pontecorvo
1957	Universal weak interaction V-A	Gell-Mann, Feynman; Marshak, Sudarshan
1957–1958	Measurement of angular correlation between an electron and a neutrino in β decay (Ar^{35}, He^6) Finally agreement obtained with V-A theory	Hermannsfeldt *et al.*
1958	The $\pi\to e\nu$ process finally observed with a probability in agreement with V-A theory	Fazzini, Fidecaro *et al.*; Impeduglia, Schwartz, Steinberger *et al.*
1958	Ionization calorimeter	Grigorov, Murzin *et al.*
1958–1963	SU(3) symmetry and weak interaction, Cabibbo theory	Gell-Mann, Levy; Kobzarev, Okun', Cabibbo
1958	Role of strong interactions in weak processes. Partially conserved axial current	Goldberger Treiman
1958	Determination of left-helicity of the neutrino	Goldhaber *et al.*
1958	β decay of polarized neutrons	Telegdi *et al.*; Robson *et al.*
1959	"Kiev symmetry," i.e., "pre-quark" lepton-hadron symmetry	Gamba, Marshak, Okubo
1962	Observation and investigation of the reaction $\mu^- + p \to n + \nu_\mu$ in hydrogen	Hildebrand
1962	Observation and investigation of the reaction $\mu^- + He^3 \to H^3 + \nu_\mu$	Falomkin *et al.*
1962–1963	Observation of $\pi^+ \to \pi^0 + e + \nu_e$ decay	Dunaĭtsev, Petrukhin, Prokoshkin *et al.*; Depommier, Mukhin, Rubbia *et al.*
1963	In experiment proposed by Gell-Mann it is found that vector current is conserved in decays of	Lee, Mo, Wu

Table II cont.

Year	Event	Author
	B^{12} and N^{12}	
1964	Nonconservation of *PC*	Christenson, Fitch, Cronin *et al.*
1964	Superweak interaction?	Wolfenstein
1967	Charge asymmetry in lepton decays of K^0_L	Dorfan *et al.*, Bennett *et al.*
1967	Exact measurement of asymmetry of electrons in muon decay	Gurevich *et al.*

TABLE III. From the birth of high-energy neutrino physics and the discovery of two types of neutrinos to the discovery of neutral currents, τ lepton, weak decays of charmed particles and the theory of electroweak interactions (1959–1980)

Year	Event	Authors
1959–1960	High-energy neutrinos. Practical proposal of neutrino experiments at accelerators which opened up a new field in the physics of weak interaction	Pontecorvo, Markov; Schwartz
1959	Spark chamber	Fukui, Miyamoto
1959–1974	Parity nonconservation in atoms?	Zel'dovich; Bouchiat, Khriplovich
1961–1962	Gauge theory of electroweak interactions	Glashow
1962	$\nu_e \neq \nu_\mu$	Danby *et al.* (Brookhaven)
1963	Magnetic "horn"	Van der Meer (CERN)
1963	Localization of neutrino interactions in emulsions with the aid of spark chambers	Burhop *et al.*
1963	Streamer chamber	Chikovani *et al.*; Dolgoshein *et al.*
1963	First neutrino experiments using a bubble chamber	Block *et al.*
1964–1967	Experimental discovery of weak nuclear forces	Abov *et al.*; Lobashov *et al.*
1964	Quarks with fractional charge (u,d,s)	Gell-Mann; Zweig
1966–1976	Electron cooling, stochastic cooling. Idea of $\bar{p}p$-collider	Budker, Skrinskiĭ, Van der Meer, Rubbia, Klein *et al.*
1964	Mechanism responsible for the origin of finite mass of vector mesons due to spontaneous symmetry violation	Higgs
1964	$\nu_\mu \neq \bar{\nu}_\mu$	Bernardini *et al.* (CERN)
1963–1964	Hadron and lepton mixing. Theoretical introduction of charm	Maki *et al.*; Nakagawa, Okonogi, Sakata, Toyoda; Bjørken, Glashow; Vladimirskiĭ; Okun'
1964–1965	Quark color; quarks with integral electric charge	Greenberg; Bogolyubov, Struminskiĭ, Tavkhelidze; Han, Nambu; Miyamoto
1964–1970	Search for $K^+ \to \pi^+ e^+ e^-$ and $K^+ \to \pi^+ \nu\bar{\nu}$ processes	Camerini, Klein *et al.* Klems, Hildebrand *et al.*
1965	Due to inelastic channels the total cross section for $\nu_\mu + n \to \mu^- + \ldots$. will probably increase with incident neutrino energy, in spite of the nucleon formfactor which limits the increase in the cross section for "elastic" scattering $\nu_\mu + n \to \mu^- + p$	Markov
1967	Quantization of Yang-Mills massless fields	Faddeev Popov; de Witt
1967–1968	Gauge model of electroweak interaction based on the Higgs mechanism	Salem; Weinberg Charpak

Table III cont.

Year	Event	Author
1968	Proportional and drift chambers	
1969	Scaling	Bjørken
1969	Parton model	Feynman
1971	Quantization of massive Yang-Mills fields. Renormalizability of Weinberg-Salam theory	G.'tHooft Rubbia *et al.*
1971	Idea of using a target-calorimeter in neutrino experiments	Rubbia *et al.*
1972	What can neutrinos tell us about partons?	Feynman
1972	GIM mechanism (fourth quark needed to explain the fact that asymmetric nondiagonal neutral currents are absent)	Glashow, Iliopoulos, Maiani
1972–1980	Total ν_μ and $\bar{\nu}_\mu$ cross sections of nucleons increase linearly with energy	CERN Gargamelle later other installations
1972–1980	Quark-parton model confirmed by measurements of charged currents in ν and $\bar{\nu}$ beams	CERN Gargamelle and later other installations
1973	Observation of neutral currents in the $\nu_\mu + e^- \to \nu_\mu + e^-$ process	CERN Gargamelle and later other installations
1973	Observation of neutral currents in muonless events $\nu_\mu + N \to \nu_\mu + \ldots$	CERN Gargamelle, Fermilab, HPW and later other installations
1973	Nucleon decay?	Pati, Salam; Georgi, Glashow
1974	J/ψ particle	Ting *et al.*; Richter *et al.*
1975	Intermediate boson mass > 17 GeV	Batavia, Cal. Tech.
1975	Detailed proposal to detect "direct" neutrinos to study production of charmed particles in nucleon-nucleus collisions	Pontecorvo
1975	First charmed baryon found in the Brookhaven hydrogen bubble chamber acted upon by neutrinos	Brookhaven, Cazzoli *et al.*
1975	$\mu^+\mu^-$ pairs found in ν_μ and $\bar{\nu}_\mu$ events show production of charmed particles by neutrinos	Fermilab-HWPF
1975	First observation of τ lepton	Perl *et al.*
1976	Mass of ν_e less than 35 eV (measurement of tritium spectrum)	Tret'yakov, Lyubimov *et al.*
1976	Observation of $\tilde{\nu}_e$-e scattering (experiment carried out using a reactor)	Reines, Gurr, Sobel
1976	Observation of elastic ν_μp and ν_μp scattering and parity violation in weak hadron neutral currents	Brookhaven-Harvard-Pennsylvania-Wisconsin; Columbia-Illinois-Rockefeller
1977	Proposal of practical utilization of recording neutrinos in nuclear power stations (measurement of power, accumulation of Pu . . ., burnup of U . . .)	Mikaelyan *et al.*
1977	Discovery of the upsilon meson, bound state of (b$\bar{b}$) quarks	Lederman *et al.*
1977	Soon after the startup of the 400 GeV proton accelerator at CERN the third generation of refined neutrino experiments with good statistics begins	CDHS BEPS and later CHARM
1978	Nonconservation of parity in atoms in agreement with the Weinberg-Salam model	Barkov, Zolotarev
1978	Scattering of polarized electrons by deuterium confirms the Weinberg-Salem model and yields a value of $\sin^2\theta_\omega$—in agreement with the best neutrino experiments of CDHS and CHARM	Prescott *et al.*
1978	Mass of $\nu_\mu \leqslant 0.57$ MeV	Frosch *et al.*
1978	Some important properties of the τ and ν_τ leptons are established: $m_\tau = 1782^{+2}_{+7}$ MeV, $m_{\nu_\tau} < 250$ MeV; V-A variant	Kirkby *et al.*; Feldman *et al.*

A large amount of work which I did not have a chance to mention has been done, and is being carried on at present in different laboratories.

Below in Tables IIIa, IIIb, and IIIc information is given concerning neutrino beams and large neutrino detectors.

TABLE IIIa. High-energy neutrino beams (as of 1980).

Accelerator	Proton energy GeV	Decay distance m	Muon shield m	Neutrino energy GeV
ANL	12,4	30	13 (Fe)	0,3 – 6
CERN	27	70	22 (Fe)	1 – 12
BNL	29	57	30 (Fe)	1 – 15
IFVÉ	70	140	62 (Fe)	2 – 30
FNAL	300 – 400	340	1000 (earth + Fe)	10 – 200
CERN	400	430	220 Fe + 150 earth	10 – 200

TABLE IIIb. Large bubble chambers (as of 1980).

Bubble chamber	Filling	Working volume m^3	Weight t
Gargamelle, CERN	CF_3Br	5	7 – 9
12' ANL (USA)	H_2, D_2	16	1 – 2
7' BNL (USA)	H_2, D_2	6	0,4
15' FNAL (USA)	H_2	20	1,3
	H_2 + Ne (20%)	20	7
	H_2 + Ne (64%)	20	22
SKAT, IFVÉ (USSR)	CF_2Br	4,5	7
BEBC, CERN	H_2, D_2, Ne	20 – 25	

TABLE IIIc. Electronic neutrino detectors at high energy accelerators (as of 1980).

Accelerator	Collaboration	Useful target weight t
CERN	Aachen-Padua	20
CERN	CERN-Dortmund-Heidelberg-Saclay (CDHS)	900
CERN	CERN-Hamburg-Amsterdam-Rome-Moscow (CHARM)	100
BNL	Harvard-Pennsylvania-Wisconsin	30
BNL	Columbia-Illinois-Rockefeller	8
IFVÉ, Serpukhov	ITÉF, IFVÉ	30
FNAL, Batavia	Harvard-Pennsylvania-Wisconsin-Fermilab (HWPF)	20
	California Institute of Technology-Fermilab	100

TABLE IV. Neutrinos in astrophysics, astronomy and cosmology (1939–1980).

Year	Event	Authors
1939	Emission of neutrons in thermonuclear reactions by the sun and other stars	Bethe
1941	Supernovae and the "URCA" process	Gamow, Schönberg
1946	Proposal of radiochemical methods for detection of neutrinos, for example the Cl^{37}-Ar^{37} method utilized in neutrino solar astronomy	Pontecorvo
1946	The theory of the hot universe (the Big Band Theory)	Gamow
1958	B^8 as a source of solar neutrinos of relatively high energy	Fowler
1959	Emission of neutrinos by hot stars is associated with the universal Fermi interaction (the $\nu + e \rightarrow \nu + e$ process)	Pontecorvo
1960	Importance of performing experiments deep underground or underwater for elementary particle physics and astronomy	Markov Greisen
1961	Phenomenological investigation of the possible existence of a "neutrino" sea	Pontecorvo, Smorodinskiĭ

Table IV cont.

Year	Event	Author
1961	Cosmological upper limit on the amount of invisible energy in the Universe	Zel'dovich, Smorodinskiĭ
1963	$\nu\bar{\nu}$ pairs and hypothetical neutral currents	Pontecorvo
1963	Large detector (atmosph.) of cosmic neutrinos placed at a depth of 8700 m.w.e. in a South African mine (8 years of measurements, 100 neutrino events)	Reines *et al.*
1964	Neutrino stars?	Markov
1965	Telescopes and magnetic spectrometers, designed to detect (atmospheric) cosmic neutrinos, are placed at a depth of 7500 m.w.e. in a gold mine in Southern India (6 years of measurement, 20 neutrino events)	Krishraswami Osborn *et al.*
1965–1966	Neutrino processes in massive stars and supernovae	Fowler, Hoyle Colgate, White
1965	Emission of recorded neutrinos ($E_\nu > 10$ MeV) in the collapse of cold stars; i.e., in the process of neutronization: $e^- + {}^zA \rightarrow \nu_e + {}^{z-1}A$	Zel'dovich
1965	Proposal of an experiment designed to record neutrinos from collapsing stars	Domogatskiĭ Zatsepin
1965	Discovery of relict electromagnetic radiation (cosmic microwave background) confirming the theory of the hot Universe (big bang theory) and requiring the existence of an analogous relict neutrino sea	Penzias; Wilson; Dicke *et al.* Zel'dovich, Novikov; Weinberg
1966	Upper limit on the mass of ν_μ obtained on the basis of cosmological data	Gershteĭn, Zel'dovich
1967	Necessity of elucidating the problem of the conservation of leptonic charge (neutrino oscillations) for the future neutrino solar astronomy	Pontecorvo
1972	What can be expected form the Cl-Ar experiment on detecting solar neutrinos on the basis of the standard model of the sun	Bahcall
1975–1977	Cosmic source of superhigh energies	Berezinskiĭ, Zatsepin
1977	Quantitative theory of supernovae in which heat from neutrinos ignites thermonuclear reactions in carbon	Gershteĭn *et al.*
1977	Scintillation telescope of the Inst. for Nucl. Res. of the USSR Acad. of Sci. is placed at a depth of 850 m.w.e. in the Baksan Valley, and has a mass of 300 *t* (3150 modules)	Chudakov *et al.*
1977	Detector of superhigh-energy neutrinos based on acoustic waves	Dolgoshein *et al.*, Sulak *et al.*
1977	Importance of neutrinos emitted by collapsing stars for nucleo-synthesis, particulary for the explanation of the abundance of proton-rich elements	Domogatskiĭ
1978	Observation of solar neutrinos with the aid of the Cl-Ar method in an experiment that has lasted for over 10 years	Davis *et al.*
1978	Cherenkov water detector (500 t) of the Pennsylvania University placed underground in South Dakota, Ohio and under Mont Blanc	Lande *et al.*
1978	Scintillation detector of the Inst. for Nucl. Res. of the USSR Acad. of Sci. (100 t) is placed in the salt mines (600 m.w.e.) in Artemovsk	Zatsepin *et al.*
1980	Scintillation detectors of neutrinos from collapsing stars (60 modules of 2 m^3 each) placed by the Inst. for Nucl. Res. of the USSR Acad. of Sci. under Mont Blanc	Collaboration Inst. Nucl. Res.-Turin University
1980	Project: optico-acoustical water detector of ~ 1 km^3 volume situated deep under water	Project DUMAND

3. PAULI

It is difficult to find an example where the word "intuition" would characterize human exploits better than in the case of the "invention" of the neutrino by Pauli.

First of all, fifty years ago only two "elementary" particles were known—the electron and the proton, and even the thought that in order to understand things it is necessary to introduce a new particle was in itself a revolutionary idea. What a difference this is compared to the present situation when masses of people are ready at the slightest provocation to invent any number of particles!

Secondly, the invented particle—the neutrino—had to have very exotic properties, in particular its colossal penetrability. It is true that Pauli did not completely appreciate such an inevitable consequence of his idea and modestly admitted that the neutrino might have a penetrability approximately equal to, or even perhaps ten times greater than, γ-rays. By the way, the theromodynamical argument based on considerations of dimensionality which shows that a neutrino of energy of 1 MeV or with a corresponding wavelength of $\lambda \approx 10^{-11}$ cm must have an astronomically large mean free path (equal to, say, a thickness of condensed matter a billion times greater than the distance from the earth to the sun) was first put forward by Bethe and Peierls.[3] In 1934 they were considering two mutually converse processes: the process of β-decay $Z \rightarrow (Z+1) + e^- + \bar{\nu}$, occurring with a characteristic time T and the reverse reaction $\bar{\nu} + (Z+1) \rightarrow Z + e^+$ characterized at the appropriate neutrino energy by the cross section

$$\sigma \leqslant \lambda^2 \frac{1}{T} \frac{\lambda}{c}.$$

Today this argument is obvious (almost all good arguments appear trivial *a posteriori*). It influenced me strongly and I did not forget it many years later when I proposed how to carry out experiments for detecting free neutrinos from reactors and the sun.[4]

Thirdly, because of its fantastic penetrability the neutrino at first appeared to be a particle which could not be detected in its free state. Its existence had to be inferred indirectly on the basis of the laws of conservation of energy and momentum, recording the recoil nuclei in β-decay with the aid of a method which is now used universally in the search for neutral particles, the so-called missing mass method. Experiments of this type were proposed by Pauli, and the first of them was carried out by Leipunsky[5] in Cambridge.

Here I would like to emphasize that fifty years ago only one fairly complex process involving a neutrino was known—beta-decay—(of heavy nuclei), as a result of which three particles appear in the final state. Ellis *et al.* showed that the average energy of the particles emitted in beta-decay (measured with the aid of a calorimeter) is equal to the average energy of the beta spectrum measured with the aid of a magnetic spectrometer. This very important point together with the fact of the existence of a maximum energy of β-rays was noted by Pauli. All other processes in which neutrinos participate were then not known. Among them there are several two-particle decays of charged particles stopped in a track chamber ($\pi \rightarrow \mu\nu_\mu$; $\mu^- + \mathrm{He}^3 \rightarrow \chi^3 + \nu_\mu$ . . .). Such decays leave "beautiful autographs" since the emitted charged particle always has the same momentum which is, of course, equal to the momentum of the invisible neutrino. Today examples of such events are, of course, well known. If such events were discovered in pre-Pauli time one would not have needed Pauli's genius to invent the neutrino. However, I would like to mention here that at the time Bohr thought that the continous beta spectrum could be associated with nonconservation of energy in individual processes, so that, strictly speaking, for the solution of the dilemma—neutrino or nonconservation of energy—one cannot use the conservation laws.

A few more words in connection with the history of Pauli's invention. Pauli himself wrote about this several decades after he had advanced his famous hypothesis which, by the way, has never been published in scientific periodical journals. Perhaps not everyone knows that the first idea of the existence of the neutrino appeared in a letter from Pauli[6] to a group of specialists in radioactivity who were planning to attend a meeting in Tübingen. The letter begins with the words: "Dear radioactive ladies and gentlemen . . ." Pauli was not present at this meeting since he had greater expectations from a ball which he wanted to attend in Zürich on the evening of December 6, 1930. However this letter contained not only jokes! It contained two ideas which could belong only to a person with the intuition of a genius. I shall now formulate these ideas both in today's and in Pauli's terminology:

1. Within nuclei there must exist electrically neutral particles—neutrons (Pauli also called them neutrons), with spin 1/2.
2. In beta-decay a neutral particle—the neutrino (Pauli gave the name neutron also to this particle) must be emitted together with the electron in such a way that the total energy of the electron, the neutrino and the recoil nucleus has a definite value.

Essentially Pauli invented two particles simultaneoulsly, with both of them being highly necessary (I have in mind, among other things,[1] the so-called nitrogen catastrophe, i.e., the proof obtained in the classical spectroscopic investigations of Rasetti that the N^{14} nuclei obey Bose statistics, so that they could hardly consist of protons and electrons.

Apparently Pauli for some time erroneously thought that his particle simultaneously could perform the function both of the neutrino and the neutron. However, he soon changed his point of view, specifically in his first official publication on the neutrino at the Solvay Congress of 1933.[7]

The next colossal step was taken by Fermi.

4. FERMI (AND POST-FERMI)

Fermi became unofficially acquainted with Pauli's hypothesis in Rome at the international congress on nuclear physics (1931) at which the problem of beta-decay was discussed. It is here that Bohr spoke in support of nonconservation of energy. Fermi was much impressed by Pauli's particle which he began to call "neutrino." As I have already mentioned, in a discussion at the Solvay Congress of 1933 which was published, Pauli for the first time spoke of his idea. At the time of the Congress Fermi, apparently, had already though deeply concerning the neutrino problem: his famous article "An attempt to construct a theory of beta-decay"[8] appeared only two months after the end of the Solvay Congress. This is a quantitative theory which had a great influence on the development of physics. There is no doubt that the idea of the existence of a neutrino would have remained a vague concept without this contribution by Fermi. The theory, with relatively small, but important and numerous additions has existed right up to the unified theory of electroweak interactions due to Glashow, Weinberg and Salam. I am convinced that, were Fermi alive, he himself would have made the majority of the necessary additions under pressure of experimental facts. About some of them I shall speak later.

I would like to relate here some curious facts associated with the appearance of this theory, facts of which I myself was a witness since at that time I was working in Rome.

1. The journal "Nature" refused to publish Fermi's pa-

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[1] The details of the theoretical notions concerning the neutron prior to its experimental discovery by Chadwick (Rutherford, Pauli, Majorana) are very interestiing, but I do not have the possibility of discussing them here. I shall only mention that Majorana, after he had read the famous article of the Joliot-Curie couple on knocking out protons from matter by the radiation from a polonium-beryllium source, noted that this is clear proof in support of a "neutral proton" (i.e., a neutron).

per since it appeared too abstract to be of interest to readers. I am convinced that the editor regretted this for the rest of his life.

2. A second curious circumstance is related to the difficulties which Fermi encountered in constructing his theory. These were difficulties not of a mathematical, but of a physical nature. The necessary mathematics, second quantization, was mastered by him quickly, but the greatest difficulty for him was the understanding of the fact that the electron and the neutrino are born when the neutron is transformed into a proton. Of course today every student knows this: the interactions between elementary particles are explained by an exchange of elementary particles. This is quantum field theory which is an unavoidable consequence of quantum theory and the theory of relativity. Particles are created and annihilated. This is what caused difficulty for Fermi. Pauli, in spite of his pioneering work in quantum electrodynamics, did not clearly formulate this concept. In reading Fermi's famous article on β-decay we see how in carrying out an analogy with the Dirac quantum theory of radiation (photons are created and annihilated!) he chose the vector variant of β-decay.

I still remember his words: when an excited sodium atom emits the 5890 Å line, the photon was not "sitting" in the atom (it was created); in just the same way when a neutron is transformed into a proton an electron and a neutrino are created.

D. D. Ivanenko arrived at the same conclusion of the creation of electrons in beta-decay in an article[9] in which for the first time an unambiguous assertion was published that the neutron is an elementary particle and not a bound proton-electron system.

With respect to the neutrino mass Perrin[10] also arrived at conclusions similar to those of Fermi. They have a very modern appearance, in the sense that both Perrin and Fermi posed the problem of the neutrino mass (a problem of primary importance even today) in an absolutely nondogmatic form and pointed out that the neutrino mass (if it is finite) can be determined by means of measuring the β-decay spectrum near its endpoint. For the most favorable case (the β-decay of the tritium nucleus) such experiments were begun with the aid of proportional counters in the 1940's.[11] A significant improvement in the determination of the upper limit of the neutrino mass was attained by Bergkvist[12] with the aid of a magnetic β-spectrometer and a very thin target. The results of measurements of a similar nature are now in the 1980's being awaited with a high degree of excitation by the entire world community of physicists after the highly interesting paper by V. Lyubimov, E. Tret'yakov *et al.* who obtained experimental indications of a finite value of the neutrino mass.[13] But let us turn back to the theory of β-decay.

In contrast to the electromagnetic interaction (mediated by a photon exchange) Fermi assumed that a contact interaction of two currents takes place—the heavy particle (n,p) current and the light particle (e,ν) current:

$$k\,(\bar{\psi}_p\gamma_\mu\psi_n)\,(\bar{\psi}_e\gamma_\mu\psi_\nu), \qquad n - \left[\begin{array}{l} \longrightarrow e^- \\ \longrightarrow \bar{\nu} \\ \longrightarrow p \end{array}\right. ,$$

where k is a constant of the order of 10^{-49} erg cm^3 (today we all know that $k = G/\sqrt{2}$, where $G = 10^{-5}/M_p^2$ is called the Fermi constant, $h = c = 1$), $\bar{\psi}_p$, ψ_n are the operators for the creation of a proton and annihilation of a neutron etc. Fermi assumed that the weak currents, as we now call them, are 4-vectors, as in electrodynamics. At first Fermi assumed that the neucleon weak current $\bar{\psi}_p\gamma_\mu\psi_n$ is analogous to the elecromagnetic current $\bar{\psi}_p\gamma_\mu\psi_p$, while the lepton weak current $\bar{\psi}_e\gamma_\mu\psi_\nu$ is analogous to the electromagnetic field. However, in his formulation the currents of the "heavy particle" and "light particle" (as Fermi called them) stand on a completely equivalent basis.

Thus Fermi erected his structure of such great perfection only on the basis of a few experimental results on beta-decay of heavy nuclei and the analogy with the Dirac theory of electromagnetic radiation.

I would like once again to emphasize that our knowledge since that time has increased tremendously; however all (or nearly all) new facts find their place in a remarkable manner within the picture drawn by Fermi.

Here are the principal post-Fermi facts.

1. Neutrinos are emitted not only in beta-decay. There are other numerous processes in which neutrinos participate: decays of the muon and the pion, lepton decays of strange particles and charmed particles, processes inverse to the preceding ones brought about by neutrino beams, tauon decays, elastic scattering of neutrinos by electrons and nucleons, deep inelastic scattering of neutrinos by nucleons. Even a small fraction of the facts enumerated above leads one to think that the Fermi interaction responsible for beta-decay is a special case of a more general 4-fermion interaction. (A separate section of the present article is devoted just to the origin of the concept of a weak process and to the first investigation of muon decay and the absorption of muons by nucleons. Further it was found that there are weak processes in which neutrinos do not participate; nonleptonic decays of strange particles and other particles, weak forces between nucleons etc.

2. There exist at least three types of leptons e, μ and τ and of neutrinos corresponding to them ν_e, ν_μ and ν_τ, two types of which have been observed in their free state by investigating their collisions with nuleons ($\bar{\nu}_e$ from reactors and ν_e from the sun and accelerators, ν_μ, $\bar{\nu}_\mu$ from accelerators). (Two sections of the present article are devoted to the radiochemical method of detecting ν_e and to the emergence of high energy neutrino physics.)

3. In weak processes there is no invariance either with respect to a change in sign of the coordinates *P* or with respect to a change in sign of all the charges *C* although the laws of nature are (almost) invariant with respect to the combined inversion *CP*, which simulataneously changes the signs of both the coordinates and the charges. Nonconservation of parity implies longitudinal polarization of particles. Thus, the theory of the two-component (or longitudinal) neutrino due to Landau, Lee-Yang and Salam was born, which is the old (1929) theory due to Weyl which now merits confidence (due to the nonconservation of parity). A good model of the neutrino according to this theory is a longitudi-

nal (i.e., rotating always to the left or to the right) screw. Goldhaber proved experimentally that the neutrino is a left-rotating particle. The antineutrino is a right-rotating particle. Thus, we have only two states, and not four, as would have been the case for a real screw (the left-handed screw, the right-handed screw, the left-handed antiscrew, and the right-handed antiscrew).

The importance of the longitudinal (massless) neutrino consists just of the fact that it indicates for us the prototype of behavior of all other (massive) fermions in weak interaction. The simple mnemonic rule can be stated as follows: in weak interaction all fermions are left-handed, and all antifermions are right-handed. The neutrino-like behavior of fermions is the principal physical content of the well-known universal weak interaction V–A of Feynman–Gell-Mann and Marshak-Sudarshan. As we have seen, the weak interaction is described in analogy with electrodynamics in terms of vector operators acting upon wave functions of particles. In this case there are two amplitudes: V-the initial Fermi amplitude which has the spatial transformation properties of a polar vector (i.e., it changes sign on inversion of coordinates), while the other amplitude A has the properties of an axial vector (does not change sign on coordinate inversion). It is the coexistence of V and A that signifies the nonconservation of parity.

Thus, the weak current which in Fermi's original paper was purely a vector, is in actual fact the sum of a vector and an axial vector (the latter is constructed with the aid of the matrix $\gamma_\mu \gamma_5$ where $\gamma_5 = i\gamma_0\gamma_1\gamma_2\gamma_3$).

Now I would like for a brief period to return to Fermi and to pose this question: what would have happened if (in 1954) Fate would have allowed him several more years of life? I think that most probably he would have invented the two component neutrino, but I am not certain of this. However, I am completely certain that Fermi would have taken the next step forward, by creating the V–A theory. He not only began all this in 1933 but in mid 1950's he, being simultaneously a theoretician and an experimenter, would have been better and more rapidly than others able to realize that those experiments the results of which were inconsistent with the formulation of a universal theory were erroneous.

4. The hadrons are mixed, i.e., in the weak interaction only the coherently mixed hadrons participate. Using the quark notation one can write the hadron charged current in the following form: $\bar{u}(d\cos\theta + s\sin\theta) + \bar{c}(-d\sin\theta + s\cos\theta) + \ldots$, where θ is the Cabibbo angle ($\sim 15°$), $\bar{u}$ is the creation operator for the u quark, d is the annihilation operator for the d-quark etc.

Thus, the weak interaction Lagrangian is: $L_w = (G/\sqrt{2})J_w J_w^+$ where $J_w = \bar{e}\nu_e + \bar{u}\nu_\mu + \bar{\tau}\nu_\tau + \ldots + \bar{u}(d\cos\theta + s\sin\theta) + c(-d\sin\theta + s\cos\theta) + \ldots$; $J_w^+ = \tilde{\nu}_e e + \bar{\nu}_\mu \mu + \bar{\nu}_\tau \tau + \ldots + (\bar{d}\cos\theta + \bar{s}\sin\theta)u + (-\bar{d}\sin\theta + \bar{s}\cos\theta)c + \ldots$ and each term is the sum of V- and A-type $\bar{e}\gamma_\mu(1+\gamma_5)\nu_e$ etc. Once again, this Lagrangian is a generalization of the Fermi Lagrangian (with insignificant but very essential additions) in which the "post-Fermi" experimental data are taken into account. It gives an excellent explanation of all the data concerning the *charged current* of which beta-decay a la Fermi was the first example. It is quite probable that not only quarks but also leptons are mixed, with important consequences relating to questions of the possibility of existence of the phenomenon of neutrino oscillations, the process of neutrinoless double beta-decay and the nature (Dirac or Majorana) of the neutrino mass. Two separate sections of the present article are devoted to these topics.

Here it should be emphasized that the theory of the longitudinal neutrino with a mass identically equal to zero describes very well all the known experimental data except for the result of the already mentioned experiment carried out by Lyubimov *et al*,[13] in ITEF (Institute of Theoretical and Experimental Physics). All experiments without exception are quite consistent with neutrinos with a mass smaller than 50 eV. At the same time the small nonzero neutrino masses are within the framework of modern theoretical concepts (I have in mind the "grand unification" of the electromagnetic, weak and strong interactions).

5. Now I should mention the most important "post-Fermi" discovery—the discovery of neutral currents made at CERN and confirmed in Fermilab using high-energy neutrino beams. I would like to say that neutral currents were being discussed long long ago, even before the theory of electroweak interactions was proposd by Weinberg, Glashow and Salam. But the discovery of neutral currents was primarily the stimulation of this theory. I shall not now go into greater detail: it would be of greater interest for the reader to read the Nobel speeches of Weinberg, Glashow and Salam.

But the phenomenological neutral currents of the symetric type $\bar{e}e$, $\bar{\nu}\nu$, $\bar{u}u \ldots$ were discussed, for example, by Bludman.[14] An investigation of symmetric neutral currents was natural. Due to the overwhelming background of electromagnetic processes nobody could prove whether such currents were present (with the exception just of the case when muonless events induced by neutrinos were being observed—the case which is the one that led to the discovery of neutral currents). I discussed even some astrophysical consequences of such currents in 1962. Of course it was clear that there are no asymmetric nondiagonal neutral currents (there are no processes of the type $K^+ \to \pi^+ + \nu + \tilde{\nu}$, $K^+ \to \pi^+ + e^+ + e^- \ldots$). I simply thought that asymmetric neutral currents are not beautiful, while the symmetric ones are beautiful. GIM had not yet been invented.

I would like to conclude with the following two remarks.

a) The very first experiment with high-energy neutrinos was carried out at Dubna with the aim of detecting just the (symmetric) neutral currents, admittedly at a level of 10^4 higher than expected from charged currents.[15] This is all that we could do using the low intensity accelerator at our disposal. But there was a hope of the existence of an anomalous interaction of ν_μ with neucleons.[16]

b) Neutral currents were sought (but they were not found!) in the course of many years, for example, at CERN, of course prior to the time when the "strategy" of Glashow, Salam and Weinberg became popular.

5. MAJORANA

In 1937 Majorana posed a very important problem in neutrino physics and generally in elementary particle physics: the problem of the true neutrality of electrically neutral fermions. I have in mind the Majorana neutrino (and the neutron!).

I feel that here it is appropriate to say a few words concerning the third giant—Ettore Majorana, whose personality can evoke great interest not only from physicists but from writers as well.

When in 1931 I came as a student of the third year in the physics Institute of the Royal University in Rome, Majorana who at that time was twenty-five years old was already well known to a narrow circle of Italian physicists and foreign scientists who worked for some time in Rome under Fermi's direction. His fame was first of all a reflection of the deep respect and admiration on Fermi's part. I remember Fermi's exact words: "If a physical problem has been formulated no one in the world is capable of responding to it better and more quickly than Majorana." In terms of the jocular vocabulary in use in the Rome laboratory the physicists, playing the roles of members of a religious order, conferred on the "infallible" Fermi the title of Pope, and on the "awesome" Majorana that of the Great Inquisitor. At seminars he was usually silent, but from time to time—and always appropriately—he interjected sarcastic and paradoxical comments. Majorana was always unsatisfied with himself (and not only with himself!). He was a pessimist, but with a very sharp sense of humor. It is hard to imagine people with such different natures as Fermi and Majorana. While Fermi was a very simple man (with a small caveat; he was a genius!) and regarded ordinary common sense a very valuable human quality (with which he certainly was endowed in the highest degree), Majorana was guided in life by very complicated and absolutely nontrivial rules. Starting with 1934 he began to meet with other physicists and to visit the laboratory at increasingly less frequent intervals. In 1938 he disappeared in the literal sense of this word. Probably he did away with himself, but there is no absolute certainty in this. He was quite rich, and I can never suppress the thought that his life might not have ended so tragically if he had to work to earn his living. Thus, the scientific activity of Majorana lasted less than ten years (1928–1937). For this reason, and also because he did not like to publish the results of his investigations, the contribution of Majorana to science is much smaller than it might have been. For example, the publication of the famous article referring to neutrino physics was aided simply by a fortunate accident. In 1937 Majorana decided to participate in a competition for a university chair. He wrote the aforementioned article simply in order to increase his chances to obtain that chair! Had not this occasion arisen the article probably never would have been published. Now I shall return to physics.

At the end of the 1950's and the 1960's an opinion was often expressed that a neutrino a la Majorana is an object although both beautiful and interesting is not realized in nature. Today one can certainly not agree with such an opinion. On the contrary, the problem posed by Majorana is becoming more and more important and now it is essentially the central problem in neutrino physics. The 1937 article in "Nuovo Cimento" is the last original paper written by Majorana. I want to discuss only the main physical and qualitative aspects of this article which was ahead of its time by approximately forty years, and I shall not touch upon its very important formal aspects. Perhaps the best course of action is to translate the abstract, the introduction and several main phrases from the article which, as far as I know, has appeared only in Italian.

THE SYMMETRIC THEORY OF ELECTRONS AND POSITRONS

E. Majorana

[Nuovo Cimento **5**, *171–184 (1937)]*

Abstract. A possibility is demonstrated of presenting the quantum theory of electrons and positrons in a completely symmetric form with the aid of a new quantization process. This alters the meaning of the Dirac equation in such a manner that there is no longer any reason for speaking of states with negative energy, nor in describing new particles (in particular neutral ones) to assume the existence of "antiparticles" corresponding to "holes" with negative energy.

The interpretation of the so-called "negative energy states" proposed by Dirac [P. A. M. Dirac, Proc. Cambr. Phil. Soc. **30**, 150 (1924); cf. also W. Heisenberg, Z. Phys. **90**, 209 (1934)] leads, as is well known, to the description of electrons and positrons which is essentially symmetric. This symmetry is entirely due to the circumstance that the aforementioned theory gives results which are indeed symmetric as long as one can avoid difficulties associated with convergence. However, artificial methods which were proposed in order to cast the theory in symmetric form corresponding to its content are not quite satisfactory either because the initial formulation is always unsymmetric, or because the symmetrization is introduced later and by methods which should be avoided (such as the cancellation of infinite constants). Therefore we have attempted to follow a new path which leads to the required goal more directly.

When we are dealing with electrons and positrons we must expect only a formal simplification of the theory; however, in our opinion, it is important (from the point of view of extending the theory to other cases) that the concept itself of negative energy states disappears. Indeed we shall see that it is quite possible to construct in a completely natural manner a theory of neutral particles without negative states.

From the first paragraph I would like to quote the following words: "... It (i.e., the newly proposed quantization method.—B.P.) is particularly important for Fermi fields, while considerations of simplicity in the case of electromagnetic field allow us to add nothing to the old methods. In the present case we shall not concern ourselves with a systematic study of the logical possibilities that are opened up from our new point of view, but shall restrict ourselves only to a description of the process of quantization, which, as far as we can see, is important for real applications. This method is, apparently, a generalization of the Jordan-Wigner method [P. Jordan and E. Wigner Z. Phys. **47**, 63 (1928)] and provides a possibility not only to cast the electron-positron theory in a symmetric form, but also to construct a completely new theory for particles without an electric charge (neutrons and hypothetical neutrinos). Although, apparently, today one cannot on the basis of experiment make a choice between the new theory and that in which the Dirac equations are simply extended to neutral particles, one should have in mind that the new theory introduces into this uninvestigated field a smaller number of hypothetical objects. . ."

From the second paragraph I quote: ". . . The advantage of this method (i.e., of the Majorana theory—B. P.) over the traditional interpretation of the Dirac equations, as we shall see below, consists of the fact that there are no longer any reasons to assume the existence of antineutrons or antineutrinos. The latter are indeed utilized in the theory of beta-decay with the emission of positrons [cf., G. C. Wick, Rend. Acad. Lincei **21**, 170 (1935)] but such a theory evidently, can be modified in such a way that the emission of positrons, as well as of electrons, will always be accompanied by the emission of neutrinos. . ."

For the benefit of the young reader, who from the very beginning of his scientific activity has been accustomed to hear not only of electrical, but also of other types of "charges" (baryon, lepton etc.), I would like to emphasize that in 1937 only the concept of electrical charge was known. It is Majorana who first explicity introduced the concept of truly neutral fermions, or Majorana particles, i.e., fermions which are identical to their own antiparitcles. The Majorana particles were called by him "two-component particles", (one particle with two spin orientations), while the Dirac particles are four component particles (particle and antiparticle each with two spin orientations). Majorana was considering "material" particles (with finite rest mass). Moreover, Majorana having posed the problem of electrically neutral fermions described either by his theory or by the Dirac theory introduced in a nonexplicit form the concept of charges differing from electrical charge. The Majorana particles are fermions which have neither electric nor any other kind of charge. The electrically neutral fermions which are not Majorana particles are described by the Dirac theory. They are not truly neutral and have some other (not electrical) charge. We note that in an explicit form the concept of baryon and lepton charges were introduced only in 1949 [17] and in 1953.[18]

From the one phrase of Majorana which I quoted above it is clear that he definitely had in mind the following question: could one establish with the aid of the experiments of the time (1937!) the nature of fermions: are they Majorana or Dirac fermions? Concerning this question I shall first of all consider neutrinos, leaving aside two very important circumstances which Majorana could not at that time have taken into account:

a) the longitudinal polarization of neutrinos,[19] associated with the nonconservation of parity (1957), and

b) the possibility of a small violation of the law of conservation of (leptonic) charge and the possibility associated with this of the existence of nonstationary neutrino states—the so-called phenomenon of neutrino oscillations[20] (in present day terminology: the eigenstates of the weak interaction Hamiltonian need not necessarily be eigenstates of the mass operator).

As one can infer from one of the quotations cited above, Majorana apparently, was thinking of experiments which, in principle, could answer the following question: are neutral leptons emitted, say, together with negative β-rays, capable of being absorbed by a nucleus with the emission again of negative electrons? I think that he did not explicitly mention such a possibility because at the time the detection of a neutrino—unfortunately—was not considered to be a serious proposal, nor even a decent topic for discussion (since the expected cross-section is laughably small!).

I personally encountered the dilemma of the Majorana neutrino or the Dirac neutrino more than once and each time it was for a long time. The first time was when I proposed and developed the chlorine-argon method for detecting neutrinos,[4] and the second time when I considered the possibility of neutrino oscillations (I shall speak of these episodes below in other sections) and again in the 1960's, 1970's and 1980's in connection with the theory of oscillations and double beta-decay.

Racah immediately reacted[21] to Majorana's paper and was the first who clearly stated the aforementioned idea on the different behavior of Dirac and Majorana neutrinos in inverse beta-decay.

Since at the time of appearance of Racah's paper uranium reactors and methods of detecting neutrinos were not yet in existence it did not exert a direct influence on the development of experiments with free neutrinos. However it should be mentioned that the theoretical interpretation of the "negative" result in the successful chlorine-argon experiment of Davis using a reactor[22] was based on an idea first expressed by Racah. At first glance Davis' result that antineutrinos from a reactor can not be absorbed with the emission of negative electrons can be interpreted (and this was the case) as a demonstration of the Dirac nature of the neutrino, or if you wish as a demonstration of the existence of a certain (non-electrical) charge of the neutrino. But as is known now such an interpretation is premature due to the important circumstances a) and b) mentioned above. I shall say a few words about this at the conclusion of this section.

Let us return to Majorana's idea. In 1938 there appeared on article by Furry,[23] which appears to me to be a typical "incubation" article. It was stimulated by the ideas of Majorana and Racah and did not contain any very important results. In this article a detailed description is given of the arguments of Racah concerning possible nuclear reactions induced both by Majorana and Dirac neutrinos.

However, it is rather pessimistic with respect to the possibility of an experimental resolution of the dilemma of the Majorana neutrino—Dirac neutrino and is a precursor of the following very wise and important article by Furry,[24] where for the first time a discussion is given of the neutrinoless double β-decay.

In the neutrinoless double β-decay the neutral lepton emitted by a neutron together with a negative electron must be absorbed by another neutron with the emission of a second negative electron. The "Racah chain" is present here, but the idea of the experiment is novel and in this case very ingenious. The search for neutrinoless double beta-decay is today, even more than in the past, very important and can provide the answer to the question concerning the nature of the neutrino (Majorana or Dirac). The neutrinoless double beta-decay has not yet been observed; bold and important experiments have been carried out and are now being carried out in order to discover it. A definite observation of such a decay would signify that the neutrinos corresponding to stationary states have a Majorana nature. A negative result of the search for neutrinoless double beta-decay cannot be easily interpreted unambiguously due to the circumstances a) and b) mentioned earlier.

Here, apparently, it is appropriate to emphasize that the negative results of experiments utilizing the chlorine-argon method using reactors, and in particular of the search for neutrinoless double beta-decay have already shown that the helicity of the neutrino (playing the role of leptonic charge) is almost if not absolutely ideal.[2)] Let us return to Majorana and now consider also the neutron.

One must only marvel as to how much explicitly or implicitly is contained in his famous article. I have already emphasized that one can find there (directly or between the lines) the electrically neutral fermions without any charge at all, or with some kind of charge (leptonic, baryonic etc.). Admittedly, all these charges are implicitly assumed to be strictly conserved, although this is not formulated. We now know that among bosons, apparently, there exist "hybrid" particles, i.e., bosons with a not strictly conserved charge,[25] oscillating between two different states, such as neutral kaons. If there exist such electrically neutral hybrids among the fermions,[20] then we are justified to expect that they are not described by stationary states, and oscillate by transforming into each other. Such particles are a superposition of particles with definite (different) masses which are described by stationary states and are truly neutral (or Majorana) fermions.

Now permit me to make a small joke and you shall see what I am driving at: neutrons and Majorana neutrinos described in the 1937 article are precursors of the fresh wind of the Grand Unification Theory with a finite neutrino mass with neutrino and neutron oscillations, neucleon decay and all the rest!

6. RADIOCHEMICAL METHODS OF DETECTING NEUTRINOS AND THE CHLORINE-ARGON METHOD

I now wish to give a subjective report on several pages in the development of neutrino physics with which I am in a certain sense associated. In 1946 neutrinos were considered, generally speaking, as undetectable particles. Many respected physicists held the opinion that the very question of detecting free neutrinos is simply senseless (and not only due to temporary difficulties) just as, say, the question is senseless of whether there can be within a vessel a pressure lower than 10^{-50} atmospheres. I well remembered the argument of Bethe and Peierls[3] and came to the conclusion that the appearance of powerful nuclear reactors made the detection of free neutrinos a completely decent occupation. I then lived in Canada and was well familiar with reactor physics. The Canadian NRX reactor in the construction of which I participated was not yet working, but it was clear to me that under a very compact shield which considerably attenuates the soft component of cosmic rays one can have a neutrino flux of the order of $10^{12}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. At that time the scintillators which many years later were so successfully utilized by Reines and Cowan[26] for the detection of reactor antineutrinos had not yet been produced. It occurred to me that the problem can be solved by radiochemical methods, i.e., by means of chemical concentration of an isotope formed in the course of an inverse beta-process from a very large mass of a substance irradiated by neutrinos.[4] After careful study of the famous Seaborg table of artificial isotopes several possible candidates for targets were found, among which the most suitable appeared to be chlorine compounds. The corresponding reaction appears as follows:

$$\text{neutrino} + {}^{37}\mathrm{Cl} \to {}^{37}\mathrm{A} + e^{-}, \tag{1}$$

where ^{37}A decays by K-capture with liberation of 2.8 keV of energy in the form of x-rays and Auger electrons. I have written here neutrino, rather than $\bar{\nu}_e$, because the question of whether ν differs form $\bar{\nu}$ was yet unclear.[3)] There are many practical arguments favoring ^{37}Cl but I shall not enumerate them here. However one of them was not known to me *a priori*, it was discovered accidentally. For testing the future neutrino detector we usually prepared ^{37}A in a reactor and placed it within the detector which, in accordance with our intentions, should be, and was in fact, a Geiger-Müller counter. And then once, glancing at an oscillograph which was connected to the counter, we saw many pulses of approximately the same amplitude from ^{37}A while the voltage applied to the counter was much below the Geiger threshold. Thus we discovered[27] (independently of Curran *et al.* in Glasgow) the proportional regime with very high gas amplification ($\sim 10^6$). This was, naturally, very important from the point of view of detecting neutrinos since it enabled us to decrease the effective background of the counter. At the same time there was a current conviction, that proportional counters cannot operate at coefficients of gas amplification higher than 100. This is naturally valid if the initial ionization (α-particles etc.) is great, but is absurd if it corresponds to only a few ion pairs.

In my paper[4] of 1946 I already considered as sources of neutral leptons not only powerful reactors, but also a concentrate of radioactive elements extracted from a reactor, and also the sun.

[2)] For the sake of clarity I wish to emphasize here that the "phenomenological" neutrino and antineutrino beams, the very words and the notations ν and $\bar{\nu}$ to which every experimenter has become accustomed, will remain in physics for a long time, even if Majorana's point of view will turn out to be correct.

[3)] This question is still not clear (1982), but now at a different level. Today the "phenomenological" answer says that $\nu \neq \bar{\nu}$ in the sense that the neutral lepton emitted in β-decay together with an electron has helicity different from the helicity of the neutral lepton emitted together with a positron in β^{+} – decay. However, as has been shown in the preceding section, such an answer does not solve the most important problem of contemporary neutrino physics: does the neutrino have a Majorana mass, in other words, are the particles described by mass eigenstates Majorana particles?

I discussed the chlorine-argon method (including the possibilities provided by the sun) with Fermi in Chicago (I think in 1948) and later in 1949 at a conference in Basel-Como. Fermi was quite unenthusiastic concerning the application of this method to neutrinos, but he liked very much our proportional counters with the aid of which we together with Hanna first observed *L*-capture in ^{37}A (250 eV, 10 ion pairs)[28] and measured the tritium spectrum lowering the upper limit for the neutrino mass by an amount which was significant at that time.[11] Looking back, I can very well understand Fermi's reaction. I think it was Segre who said that Don Quixote was not one of Fermi's heros. He could not regard with sympathy an experiment which, although it did have a brilliant conclusion due to the heroic efforts of R. Davis,[22] but only many, many years after it was first conceived.

Now I shall return to the question of whether the reactor antineutrinos can initiate reaction (1). Sometime in 1947 or 1948 I was passing through Zürich and had lunch with Preiswerk and Pauli. I told Pauli about my plans concerning the chlorine-argon method. He very much liked the idea itself and he noted that it is not clear whether the "reactor neutrinos" would sufficiently effectively initiate reaction (1), but in his opinion they apparently should. (As you can see this is Majorana's point of view). Up to 1950 I continued to think about this problem testing proportional counters with low background, having in mind both that problem and the problem of the sun. I remember that Camerini who at the time was working in Bristol and was a big specialist on "stars" formed by cosmic rays helped me to calculate the cosmic background in different chlorine-argon experiments which I was planning to conduct. In any case, as we now know after recent successful experiments of Davis the effective background in my counters was sufficiently low that one could record solar neutrinos by the decay of ^{37}Ar. From 1950 onwards I stopped doing such experiments since I came to work in an accelerator (and not in a reactor) laboratory, and also because in the USSR there were no sufficiently deep underground laboratories suitable for solar experiments (by the way, it will soon be possible to engage in this enterprise at the Baksan neutrino observatory in the vicinity of El'brus in the Caucasus). Nevertheless I continued all the time to think about counters (. . . and about the sun) and, when I had the pleasure of meeting R. Davis at the first neutrino conference in Moscow (1968) I expressed the opinion that a measurement of the shape of the pulse from the counter in addition to measuring the amplitude should lead to a significant lowering of the effective background in such solar experiments. And it did turn out to be that way, as I found out later from R. Davis at the "Neutrino-72" conference in Hungary.

Since we have touched upon the interpretation of experiments with solar neutrinos I shall discuss in the next section the possible phenomenon of neutrino oscillations which, if it exists, will play an important role in neutrino physics and neutrino astronomy.

7. NEUTRINO OSCILLATIONS AND THE SUN

In 1957–1958 I considered for the first time oscillations of the type muonium⇄antimuonium, and it became clear to me that oscillations in particle physics can occur not only in the case of bosons ($K^0 \rightleftarrows \bar{K}^0$, $\mu^+e^- \rightleftarrows \mu^-e^+$), but also in the case of electrically neutral fermions. In my opinion a good candidate for this would be neutrino oscillations.[20] At that time it was not yet known that there exist at least two types of neutrinos. Then the theory of longitudinal (two-component) massless neutrinos, which does not admit oscillations, was dominant. But if there are deviations from the theory of longitudinal neutrinos, then neutrino masses are finite and oscillations can occur. In accordance with this I considered oscillations (of maximum amplitude) $\nu \rightleftarrows \bar{\nu}_{\text{ster}}$ and in accordance with this introduced the concept of neutrino sterility. In this case particles with definte masses are two Majorana particles ν_1, ν_2 with different masses m_1 and m_2 with the length of the oscillations being expressed in terms of m_1 and m_2 and the neutrino energy $E \gg m_1, m_2$.

I returned to the problem of neutrino oscillations in mid 1960's. At the time it became quite clear to me that the possible phenomenon of oscillations is of great importance for designing experiments on the problem of finite neutrino masses and the possible nonconservation of leptonic charge, and also for astrophysics. I did not see any principle requiring zero neutrino mass, and therefore a small but finite neutrino mass appeared to me to be a no less beautiful possibility than zero mass. Is the neutrino (zero mass!) distinguished among the fermions or not (finite mass!)—this is a question which should be answered by an experiment. At that time I was working on the problem of neutrino oscillations in close contact with members of ITEF I. Kobzarev and L. Okun' to whom I would like to express here my deep gratitude, and also with I. Pomeranchuk who departed from us prematurely in 1966.

In 1967 I was invited to write an article for a book being published in honor of the sixtieth birthday of G. Bernardini; already being "enthused" by neutrino oscillations I wrote an article on oscillations.[29] By the way, in this article my original idea (1957–1958) concerning neutrino oscillations was generalized to the case of two types of neutrinos ($\nu_e \rightleftarrows \nu_\mu$ oscillations). This generalization was then a trivial addition to my papers of the 1950's, but in the 1967 paper I for the first time discussed problems which are still of interest now: 1) the exceptionally high sensitivity of the oscillation method for obtaining information on extremely low values of neutrino masses, 2) design of experiments on neutrino oscillations using reactiors, accelerators and cosmic rays, 3) conditions under which oscillations of the lepton number lead to flavor oscillations ($\nu_e \rightleftarrows \nu_\mu$), 4) conditional neutron sterility, due to the threshold effect (ν_μ of low energy) and, finally, 5) the high degree of importance of neutrino oscillations for future experiments in the field of neutrino astronomy of the sun (in the presence of oscillations half of the neutrinos emitted by the sun can transform into undetectable particles[4]).

In 1967 it was not known to me that Nakagawa, Okonogi, Sakata and Toyoda had already in 1963 introduced lepton mixing with an arbitrary angle.[30] These authors also did

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[4] As has been noted by Pomeranchuk, nontrivial temporal variations in the intensity of solar neutrinos can also arise related to the fact that the distance from the sun to the earth varies with time, and the variation of this distance may be comparable with the length of the oscillations.[29]

not know of my work of the 1950's on neutrino oscillation. The work of the Japanese authors is rich in new ideas[5)] on the mixing of hadrons and leptons. However, in contrast to the Dubna work of the 1950's–1960's it did not exert any significant influence on the development of the physics of neutrino oscillations and was not accompanied by a flow of theoretical and experimental investigations or proposals of experiments either by the authors themselves or by other physicists. In the excellent review by P. Frampton and P. Vogel[32] (1982) one can read the following words: "Neutrino oscillations between different flavors could be seriously discussed only after experimental proof that there exists more than one type of neutrino: theoretical papers by Maki, Nakagawa and Sakata appeared in Japan (1962) and by Pontecorvo in the USSR (1967)." I cannot agree with this assertion which by a simple nonrecognition of the right of existence of neutrino oscillations of lepton number reduces to naught my papers of the 1950's. What is wrong with mixing of Majorana fields?

It is correct that for existence of neutrino oscillations it is necessary to have at least four states: this minimum can be realized either in the case that there exist two flavors (ν_e and ν_μ), or in the case of only a single flavor (two active and two sterile states). The first quantitative (or if you wish, serious) discussion of neutrino oscillations was given in 1968 in the paper "Neutrino astronomy and leptonic charge",[33] when V. Gribov became interested in the problem. This paper exerted a decisive influence on all subsequent theoretical and experimental work in the field of neutrino oscillation physics. A couple of words concerning the paper in which a simple and rigorous count of the number of neutrino states was made for the first time. In it a discussion is given of the general case of oscillations in the presence of four, and only four, neutrino states. In the zero order approximation of the theory[33] there are two (two-component) neutrinos with zero masses (four states in all). The mass term which takes into account phenomenologically all possible and virtual transitions, which violate the conservation of leptonic charge, consists of three terms. The first of them which contains the parameter $m_{\bar{e}e}$ (with the dimensionality of mass) corresponds to transitions with violation of the leptonic charge of the electron L_e; the second term which contains the parameter $m_{\bar{\mu}\mu}$, corresponds to the violation of the muon leptonic charge L_μ, while the third term expressed in terms of the parameter $m_{\bar{\mu}e}$ corresponds to transitions in which L_e and L_μ are not conserved, but $L_e + L_\mu$ is conserved. It turns out that the particles with the definite masses m_1 and m_2 are the two Majorana neutrinos ν_1 and ν_2, or, as is appropriately said today, two neutrinos with Majorana masses. Thus, the introduction of an interaction which does not conserve leptonic charge is equivalent to orthogonal mixing with an arbitrary angle θ of the massive fields of the Majorana neutrinos.

A beam of neutrinos, say ν_e, formed as a result of the usual weak process, is described not by a stationary state, but by a superposition of stationary states. The mixing angle θ and the masses are expressed in terms of the parameters of the theory in the following manner:

$$\operatorname{tg} 2\theta = \frac{2m_{\bar{\mu}e}}{m_{\bar{\mu}\mu} - m_{\bar{e}e}}, \tag{1}$$

$$m_{1,2} = \frac{1}{2}\left(m_{\bar{e}e} + m_{\bar{\mu}\mu} \pm \sqrt{(m_{\bar{e}e} - m_{\bar{\mu}\mu})^2 + 4m_{\bar{\mu}e}^2}\right). \tag{2}$$

If $W_{l'l}(R)$ is the probability of finding $\nu_{l'}$ with momentum P at a distance R from the source of ν_l and

$$L = 4\pi \frac{P}{m_1^2 - m_2^2} -$$

is the length of the oscillations ($p \gg m_1, m_2$), then we have

$$W_{\nu_e,\nu_e}(R) = 1 - \frac{1}{2}\sin^2 2\theta\left(1 - \cos 2\pi\frac{R}{L}\right), \tag{3}$$

$$W_{\nu_e,\nu_\mu}(R) = \frac{1}{2}\sin^2 2\theta\left(1 - \cos 2\pi\frac{R}{L}\right). \tag{4}$$

Oscillations occur if $\theta \neq 0$ and $m_1 \neq m_2$. Under particular (quite attractive[34]) conditions $m_{\bar{e}e} = m_{\bar{\mu}\mu}$ or $m_{\mu e} \gg m_{\bar{e}e}$ the oscillations have a maximum amplitude ($\theta = \pi/4$), just as in the case of the oscillations of K^0 mesons. Relations analogous to (1), (2), (3), (4), also hold for the case of only a single flavor, but only for four states (two active states, say ν and $\bar{\nu}$, and two sterile states, $\bar{\nu}_{\text{L ster}}$, ν_{Rster}); as before the eigenstates of the mass correspond to two neutrinos ν_1 and ν_2 with Majorana masses: in the case of maximum amplitude—these are the $\nu \rightleftarrows \bar{\nu}_{\text{L ster}}$ oscillations which I discussed in 1958.

I would like to say here a couple of words concerning the neutrinos from the sun. Measurement of the intensity of the neutrinos from the sun is an exceedingly sensitive method of searching for neutrino oscillations.[35] This is associated with the fact that the energy of the solar neutrinos is small, while the distance between the earth and the sun is tremendous. It is often stated that for the interpretation of the so-called solar neutrino puzzle, i.e., the discrepancy between the intensity of the neutrinos from the sun measured by Davis by the chlorine-argon method compared with that calculated by Bahcall on the basis of the standard model of the sun, I had given an *ad hoc* explanation in terms of neutrino oscillations. The actual course of events was somewhat different. In actual fact I, having acquired a belief in the possible reality of neutrino oscillations, predicted,[29] that one might observe a deficiency up to a factor of 1/2 of neutrinos from the sun in future experiments by Davis. I wish very much that the "solar neutrino puzzle" would turn out to be real, but I am afraid today, just as many years ago, that the expected intensity of the neutrinos from the sun is for objective reasons insufficiently well known for a confident assertion of a deficiency.

By the way, in the 1970's I found an additional mechanism[36] increasing the possible deficiency of solar neutrinos being recorded. At that time only two flavors of neutrinos were known, since the τ lepton had not yet been discovered. I investigated the possibility of existence of new leptons and showed that if N types of neutrinos are present whose fields are maximally mixed, then the intensity I of solar neutrinos being detected will be by a factor of N lower than the intensity I_0 expected in the absence of oscillations. This possibility has been widely discussed in recent years in connection with

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[5)] The papers[30] of Nakagawa *et al.* became known to Bilen'kiĭ and myself in 1977. We commented on their work positively in our review on oscillations.[31]

the "solar neutrino puzzle." Of interest are the concluding words of my original paper "Heavy leptons and neutrino astronomy" [Pis'ma Zh. Eksp. Teor. Fiz. **13**, 281 (1971); JETP Lett. **13** 199 (1971)]: "Fortunately the theoretical scheme which might have led to such a sad ($I = I_0/N$—B.P.) consequence for observational neutrino astronomy is esthetically unattractive, and one can hope that it is not realized in nature." I still think so today.

Quantitatively the question of oscillations in the presence of N flavors of neutrinos was discussed by Bilen'kiĭ and myself[37] for the general case when, in addition to oscillations of flavor there also occur oscillations of the lepton number (so that sterile states coexist with active states). The number of massive Majorana neutrinos in this case is equal to 2N, and in the case of maximum mixing only the fraction $1/2N$ of all the neutrinos can be detected. We know at present three flavors of neutrinos, so that the intensity of detectable solar neutrinos may fall to a value as low as 1/6 of total intensity. Again it seems improbable that such a possibility would be realized in nature. Recently Bilen'kiĭ and myself have discussed a more realistic case,[34] when the detectable number of solar neutrinos is equal to 1/2 of the total number of neutrinos.

The following part of the present section is polemical in nature. It touches upon questions of priority. I have written it for specialists. Perhaps one should not have spoken about this, if the Dubna papers of the 1950's, and also of the 1960's and 1970's were not ignored or distorted by some physicists and authors of popular articles. The subject of neutrino oscillations, or more exactly the question of priority in the field of oscillations has appeared in such well known journals as "Physics Today," "Scientific American," "Science News" and others, and I hope that this fact will justify my ridiculous tirade!

And so, in the summer of 1980 I was in Italy at major international conferences on neutrino physics in Erice and on elementary particle physics in Trieste. In some papers on neutrino oscillations the Dubna papers were in fact ignored by some authors. This appeared to me to be all the more strange because the content, the formulas, the phenomenology and even sometimes the jargon in these papers were to a large extent those of Dubna. I even consoled myself by the thought that perhaps our papers are so well known that they already no longer have to be quoted. But I was wrong. On returning to Dubna I began to read the literature starting with the spring of 1980. From a number of articles published in different serious scientific and popular-science journals I learned that my papers of the 1950's are not of interest and, in particular, that I am not accorded priority in neutrino oscillations. What was the matter? I understood this later when I had the opportunity to see the transparencies, and later to read the paper of Sandik Pakvasa at the XX International Conference on High Energy Physics on 17–23 July, 1980 (Madison, Wisconsin): "my fault" consists of the fact that in the 1950's I did not discuss oscillations of neutrino flavor.

I must here say a few words since my articles of the 1950's were misrepresented in the paper by S. Pakvasa.[38] If I make no reply, it might be thought that I agree with him. In brief, S. Pakvasa asserts that I proposed "real oscillations" $\nu_{eL} \rightleftarrows \bar{\nu}_{eR}$. But there are no such oscillations and they cannot occur. I never expressed myself in such words. They belong entirely to S. Pakvasa. I well understand that today people do not have the time even to read the articles which they quote. However if S. Pakvasa did want to discuss the content of my work having in mind the question of priority, then he should have been obliged to make neither additions nor significant omissions. I must quote some passages from my papers of 1957–1958 written at the time when only one type of neutrino was known in order to prove what I have in mind.

"If the theory of the two-component neutrino were to turn out to be invalid (which at the present time appears to be improbable) and if the law of conservation of neutrino charge were not to hold (this is to be understood as the law of conservation of leptonic charge—B.P.) then the neutrino–antineutrino transitions in vacuum are in principle possible" [Zh. Eksp. Teor. Fiz. **33**, 551 (1957); Sov. Phys. JETP **6**, 431 (1958)].

"From the assumptions that have been made it follows that the neutrino can be transformed in vacuum into an antineutrino and vice versa. This means that the neutrino and the antineutrino are "mixed" particles, i.e., the symmetric and antisymmetric combinations of two truly neutral Majorana particles ν_1 and ν_2 having a different combined parity" [Zh. Eksp. Teor. Fiz. **34**, 248 (1958); Sov. Phys. JETP **7**, 172 (1958)].

"Thus, if R (the length of the oscillations—B.P.) is $\leqslant 1$ m in the experiment of Cowan and Reines the cross section for the production of neutrons and positrons when hydrogen absorbs neutral particles from the reactor must be lower than the cross section expected on the basis of simple thermodynamic considerations. This is related to the fact that the flux of neutral leptons which at the instant of their production is capable to induce a reaction with a certain probability alters its composition on the way from the reactor to the detector. It would be extremely interesting to perform the experiment at different distances from the reactor. On the other hand it is difficult to predict the effect of real antineutrino—neutrino transitions on the experiment of Davis since here we are not dealing with a strictly inverse beta-process and such unknown factors may turn out to be essential as polarization and energy dependence of the polarization of neutral leptons from the reactor and from the A^{37}–Cl^{37} transition" [Zh. Eksp. Teor. Fiz. **34**, 248 (1958); Sov. Phys. JETP **7**, 172 (1958)].

"The effects of transformations of neutrinos into antineutrinos might be unobservable in the laboratory due to the large value of R, but will occur on the scale of astronomical distances" [Zh. Eksp. Teor. Fiz **34**, 249, (1958); Sov. Phys. JETP **7**, 173 (1958)].

Perhaps S. Pakvasa did not understand the point of my articles. But then how could he have become a coauthor of the article by V. Barger, P. Langacker, J. P Leveille and S. Pakvasa [Phys. Rev. Lett. **45**, 692 (1980)]? And indeed, the principal content of this article is the introduction of neutrino sterility which I already made in 1958, and the quantitative description of neutrino oscillations in the general case of N active and N sterile neutrinos that had already been given in the Dubna articles[37] of 1976 (together with the aforementioned applications to the sun). By the way, these oscillations were in 1980 for some reason named by S. Pakvasa *et al.* as "oscillations of the second kind." It appears to me most probable that due to his preconceived notions S. Pakvasa in 1980 did not wish to, or could not, believe that in 1958 I invented sterile neutrinos and perfectly "lawful" neutrino oscillations.

In conclusion I would like to note that today the problem of neutrino oscillations is a very urgent one, and all over the world experiments on looking for this phenomenon are either being carried out or being prepared. From the theoretical point of view finite neutrino masses and neutrino oscillations would be welcomed by the adherents of the Grand Unification of weak, electromagnetic and strong interactions, i.e., by the majority of physicists. From the experimental point of view today there are no final indications concerning the existence of oscillations. The next generation of experiments with solar neutrinos is the most promising avenue.

In Dubna we became firmly convinced in the importance of oscillations, and, in particular, made systematic reports at major international conferences[39] concerning oscillations, even before this subject had become fashionable. We have not changed our opinion.

8. THE CONCEPT OF WEAK INTERACTION AND "ANCIENT" INVESTIGATION OF MUON PROPERTIES

Many physicists do not know that after the discovery of radioactivity approximately fifty years had to pass before the concept of weak interactions was born and received universal acceptance. I shall speak below about a short stage in this period which is associated with the development of our knowledge concerning the properties of muons and which began with the famous experiment of Conversi, Pancini and Piccioni.[40]

I was working in Canada when I first heard of this experiment. Until 1947 cosmic ray physics was for me a very distant field. Some information about it I obtained from my friends: in Florence from Bernardini and Occhialini, in Paris from P. Ehrenfest, Jr. (a very promising experimenter who worked in the group of Auger that were studying cosmic rays, and who prematurely lost his life in the mountains) and in Montreal from Rasetti (one of my teachers who in Quebec was the first to measure directly the lifetime of the "mesotron") and from Auger (who carried out similar measurements together with Maze and under whose direction I was working in Canada during the war).

And so, as soon as I had read the article of Conversi *et al.* and learned about the considerations of Fermi *et al.* on this question,[41] I was literally captivated by the particle to which we now refer as the muon. It was indeed an intriguing particle: "ordered" by Yukawa and discovered by Anderson, as Conversi *et al.*, discovered, in actual fact had nothing whatsoever to do with the Yukawa particle! I felt myself carried away by an antidogmatic wind and started asking numerous questions of the type:

—Why should the muon spin be integral?

—Who says that the muon must decay into an electron and a neutrino, and not into an electron and two neutrinos or an electron and a photon?

—Is the charged particle emitted in muon decay an electron?

—Are other particles in addition to an electron and a neutrino emitted in muon decay?

—In what form is energy liberated when a muon is captured by a nucleus?

The question associated with muon capture I answered almost at once[42] and, as it later turned out, correctly, noting that the rates of nuclear capture of an electron and a muon are very close to one another (if one takes into account the difference in the volumes occupied by the electron and the muon orbits). The answers were as follows:

1) muon capture must be a process practically identical to the beta process and is described by the reaction[6)] $\mu^- + p \rightarrow \text{neutrino} + n$;

1) the greater part of the energy liberated in muon capture is "invisible" since it is carried away in the form of a neutrino—an assumption which was experimentally confirmed and agrees with the first answer:

3) the spin of the muon must be 1/2.

A very difficult step for me was the explanation of the copious production of muons by cosmic rays. I was convinced that the muon is a fermion. A fermion cannot be created by itself. The assumption concerning copious production of muons-neutrino pairs contradicted my principal conclusion that the muon-neutrino coupling to the nucleus is weak. I had to turn to the theory of Marshak on nuclear forces arising as a result of exchange of pairs of charged leptons. In actual fact I did not understand this theory and did not achieve my aim—did not elucidate the true source of muons. Such a source had to be a "muon-pregnant" object as Weisskopf picturesquely and precisely stated,[43] who for some reason also did not achieve the goal. Such an object is, of course, the pion. The correct answer was soon given by Marshak and Bethe[44] in their remarkable article "On the two meson hypothesis," published approximately at the time when the epoch-making discovery of the pion and the $\pi - \mu$ decay occurred (Lattes, Occhialini and Powell).[45]

The fact that the processes of capture by a nucleus of a muon and of an electron are very similar, i.e., that both are "weak processes," was absolutely clear at the time to myself and to some other physicists.[46] Such an electron-muon symmetry was the first hint concerning a universal weak interaction (but how far this was from the form of such interaction found in 1958, i.e., from V–A theory due to Marshak-Sudarshan and Feynman–Gell-Mann,[47] supplemented by the Cabibbo mixing angle!).

As regard questions associated with muon decay they could be answered only with the aid of appropriate experiments. I became actively interested in the physics of cosmic rays, and rapidly read and assimilated the very fine brief

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[6)] Fifteen years were needed for a definite observation of the reactions $\mu^- + p \rightarrow n + \nu_\mu$ and $\mu^- + He^3 \rightarrow H^3 + \nu_\mu$ respectively in the experiments of R. Hildebrand and in our experiments together with R. Sulyaev *et al.*

brochure on cosmic rays published by Heisenberg,[48] something like a guidebook for beginners. Together with Ted Hincks, a remarkable physicist endowed with a wonderful sense of humour, we began collaborative experiments. This was a very friendly, unforgettable and fruitful collaboration. In a short period we constructed an apparatus quite complicated for the time. We used methods of instantaneous and delayed coincidences and, naturally, Geiger counters were used as dectectors. We were working in a reactor laboratory and therefore had a certain feeling of guilt occupying ourselves with cosmic rays. It must be said that our Division Head, B. Sargent, (the physicist who discovered the rule relating the probability of β-decay to the energy of the emitted electrons) maintained a favorable attitude to our activity. And still I cannot forget how unwillingly Ted and I expended laboratory facilities and how happy we were when Ted invented the "threshold amplifier" which enabled us to economize on the number of counters, having made it possible to increase significantly the efficiency of the detection of photons emitted simultaneoulsy with electrons in the hypothetical $\mu \rightarrow e + \nu$ decay. And, incidentally, the amounts spent on all our research on cosmic rays in Canada were infinitesmal in comparison with what is now expended on a typical experiment in the field of high energy physics in the course of a few hours.

We found: 1) that the $\mu \rightarrow e\gamma$ decay does not occur (we were looking for delayed electron-photon coincidences[49]); 2) that in muon decay three particles are emitted e, ν, ν' (we measured the electron spectrum by the absorption method)[50]; 3) that the charged particle emitted in muon decay is indeed an electron (we measured the intensity of its bremsstrahlung).[50] The first two results were obtained independently of ourselves also by other groups of authors.[51,52] The third result was obtained only by our group. It is this result that required from us the maximum of effort and ingenuity, while from the current point of view it might appear to be the least significant: what else other than an electron can be the charged particle in muon decay? However, one should take into account the strong "antidogmatism" characteristic of that time. The atmosphere of doubt in which we lived can be felt in the title of one of our papers: "On the stability of the neutral meson." In this paper[53] we showed that a neutral meson the existence of which at that time was considered to be possible, either is not emitted at all in muon decay, or its lifetime for the decay into two photons is not less than 10^{-10} s.

In concluding these far from complete and subjective reminiscences concerning some early muon investigations I must mention a theoretical paper which was, and remains even up to now, very important: the introduction by Michel of the parameter ρ for muon decay,[54] or, in a more general sense, the description by Michel of processes in which two real neutral leptons participate.

After the appearance of the first accelerators in the relativisitic energy domain pions and muons began to be obtained artificially. In the 1950's their properties were begun to be investigated under conditions incomparably more favorable than earlier ones, but I do not intend to tell this story, the climax of which was the epoch-making (theoretical[19] and experimental[55]) discovery of neutrino helicity.

9. HIGH-ENERGY NEUTRINO PHYSICS

My story here will again be very personal. Of course, the story would appear quite different if it were told by M. A. Markov or M. Schwartz. I intend to relate how I arrived at the proposal to carry out experiments with high-energy neutrinos obtained in meson factories and very high energy accelerators.

In the Laboratory for Nuclear Problems of the JINR in 1958 a relativistic proton cyclotron was being designed with a beam energy of 800 MeV and a current of 500 μA. In the end this accelerator was not built. But from the beginning of 1959 I started thinking about an experimental program for this accelerator. First of all it occurred to me that neutrino experiments using an accelerator are quite feasible and that a viable relatively cheap neutrino program can be carried out by "dumping" the proton beam into a large iron block which could simultaneously serve as a neutrino source and a shield. I might say that the ideology of neutrino experiments at the LAMPF accelerator which began recently is very similar to the program proposed by myself more than 20 years ago for the accelerator which has never been built.

I would like to say a few words concerning one of the experiments which was intended to answer the question as to whether ν_e and ν_μ are different.

I must go far back to 1947–1950. Several groups, among them J. Steinberger, E. Hincks and myself, were carrying out research on muon decay in cosmic rays. As a result it was found that the decaying muon emits three particles: one electron (this we established by measuring the electron bremsstrahlung) and two neutral particles to which different persons gave different names: two neutrinos, a neutrino and a neutretto, ν and ν' etc. I am again speaking of this emphasizing that for people working with muons in past times the question of the different types of neutrinos was ever present. It is true that later many theoreticians forgot about this and some of them again reinvented two neutrinos, but such people as Bernardini, Steinberger, Hincks and myself had never forgotten the two neutrino problem. Of course the formulation of the problem became for me more and more exact: the idea appeared of possible partners, in the sense that ν_e always appears as the partner of an electron, and ν_μ as that of a muon. I formulated quite clearly how to carry out a crucial experiment utilizing muon neutrino beams.[56] It was proposed to look for muons and electrons created in matter by muon neutrinos; if $\nu_e \equiv \nu_\mu$, then it should turn out that there should be many fewer electrons created than muons.

In 1959 another problem was very important: is the four-fermion interaction a contact interaction or is it mediated by the exchange of an intermediate boson? This question is still open today, but now we have the theory of Glashow, Salam and Weinberg which predicts that the masses of the intermediate bosons must be approximately 100 GeV.

In 1959 only some scientists, among whom were Ya. Zel'dovich and J. Leite Lopes, thought that the intermediate meson has a mass of ~ 100 GeV, while usually it was considered (without any serious basis for this) that its mass is a few GeV.

It is evident that the intermediate boson could not be produced in meson factories, and in 1959 at the international conference in Kiev Ryndin and myself proposed a second idea for an experiment: to look for the boson utilizing neutrino beams obtained at very high energy accelerators.[57] Theoretically this proposal was based on the fact that at sufficiently high energies G instead of G^2 should appear in the cross section for the production of the intermediate boson with the aid of a neutrino. As is well known, the question of the intermediate bosons will be solved not in neutrino experiments but in $\bar{p}p$-colliding beams. The problem of the two types of neutrinos was solved in Brookhaven in the brilliant experiments of Lederman, Schwartz, Steinberger *et al.* (1962).

10. DIRECT NEUTRINOS AND "BEAM-DUMP" EXPERIMENTS

The method of "beam-dump" experiments consists of recording "direct" (i.e., not coming from the decay of kaons and pions) neutrinos from lepton decays of short-lived particles, say from charmed particles.[58] In "beam-dump" experiments which were carried out in Serpukhov and at CERN (by four groups) the production of charmed particles in nucleon-nucleon collisions was first observed and investigated.

This is a miracle which in order to appreciate you might be helped by an analogy with other hypothetical cases: imagine that when Rutherford first observed the β-decay of nuclei he detected not electrons but observed neutrinos from a source of intensity $\gg 10^9$ Ci! Or imagine that Lattes, Occhialini and Powell first observed pion decay after they had designed and built a modern installation for high-energy neutrinos (a proton accelerator, a decay tunnel, an iron shield and a multiton neutrino detector) instead of simply observing muons coming from pion decay!

11. AN ALTERNATIVE SCENARIO OF THE DEVELOPMENT OF NEUTRINO PHYSICS?

I would now like to present to you a scenario for the development of weak interaction physics which was not realized, but which, in my opinion, could have been realized. Such a scenario may perhaps exasperate those readers who work in the field of very high energy neutrino physics. By the way, I'm playing the role of the devil's advocate since I myself have a great love of high energy neutrino physics.

I know a great scientist, Petr Leonidovich Kapitsa, who now thinks that if an experiment is too expensive and awkward it should not be performed: with the passage of time the problem will be solved more simply. Let us assume that in the beginning of the 1960's the community of physicists would have concluded that neutrino experiments at very high energies are too expensive and too awkward. Further let us suppose that this community would hold the following opinion: that neutrino physics could be developed in a relatively inexpensive manner at "meson factories" of which more and more are being built, and also at nuclear reactors. Also let us assume that the "world ministry of science" in the 1960's had decided not to provide financing for high-energy neutrino physics, at the same time contributing to the development of neutrino physics at low and intermediate energies. One need not have a great imagination in order to reply to the question of what kind of successes would have followed from this. For comparison let us consider the path indicated by the essential results of neutrino physics at very high energies:

1. $\nu_e \neq \nu_\mu$: this result would have been obtained at a "meson factory," but at least 10 years later. By the way, ν_τ was discovered in experiments on colliding electron-positron beams:

2. Nucleon structure: without experiments with neutrino beams of very high energy our knowledge would have been incomplete. However, at the same time one should not forget the very important information obtained in the study of deep inelastic scattering of electrons (and of muons) by nucleons.

3. Neutral currents: they have been discussed by a number of physicists from the phenomenological point of view even prior to the theory of electroweak interaction. This theory, without a doubt, was created independently of experiments with high-energy neutrinos. Conservation of parity in atoms predicted by Zel'dovich[59] was observed in Novosibirsk[60] in agreement with theoretical expectations of Glashow-Salam-Weinberg. This is a difficult and beautiful experiment, but a cheap one. The beautiful experiment,[61] carried out at SLAC on the scattering of polarized electrons by nucleons gave an exact value of $\sin^2\theta_w$. Neutrino experiments on neutral currents are at present being carried out or planned at reactors and meson factories. Of course, if experiments on neutral currents using high-energy neutrinos had not been carried out at CERN, exact values of $\sin^2\theta_w$ would not have been available, and this would have been a serious loss.

4. Without neutrino experiments at very high energies the production of strange and charmed particles by neutrinos would not have been investigated. However, the greater part of our knowledge in physics associated with lepton decays of strange and charmed particles was obtained by means of investigations using hadron beams and electron–positron colliding beams.

Thus, I summarize: what has in fact occurred in high energy neutrino physics is not inexpensive, but is very valuable. The expenditure of resources has been justified, but one should neither underestimate the importance of high-energy neutrino physics, nor overestimate it. This is not pessimism, but an appeal to avoid routine.

12. CONCLUSION

In contrast to the time when high-energy neutrino physics was only being born, 20 years ago, at present it is a healthy and prominent field in physics, in which the quantitative aspect dominates. The fact that neutrinos are difficult to detect (in contrast to other long-lived particles) has as a result that research in high energy neutrino physics is unusually complex and expensive. Therefore the program for investigations using beams of very high energy neutrinos must be developed very carefully.

Not only new ideas in designing experiments are required, but also new ideas in the production of beams (tagged neutrinos? . . .) and detectors (gigantic liquid detectors? . . .).

It is not accidental that three of the most promising experiments in neutrino physics the results of which are being impatiently awaited all over the world, lie outside the field of high energy physics:

1. Exact measurement of the beta-spectrum of tritium.
2. The search for neutrinoless double beta-decay.
3. The search for oscillations of solar neutrinos.

The existence of finite neutrino masses would be of importance for elementary particle physics, but also would produce a revolution in cosmology, astrophysics and neutrino astronomy of the sun.

Below are listed some of the main problems of the neutrino physics of today. These problems are, of course, interrelated.

1. Are the neutrino masses finite?
2. Are all the neutral leptons much lighter than electrons?
3. If the neutrino masses are finite do they all have the Majorana mass (in this case there are no lepton charges) or do they all have the Dirac masses? Perhaps some neutrinos have Majorana masses and others have Dirac masses?
4. How many different types of neutrinos are there?

These questions have been open for a long time. However it does not appear as if definite answers to *all* these questions will be obtained in the near future.

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Translation Editor's note: The translator wishes to dedicate this translation to the memory of the recently deceased E. P. Hincks (cf. Sec. 8 above and Refs. 49, 50 and 53) who was a close personal friend of both the author and the translator.

Translated by G. Volkoff