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FIFTY YEARS OF NEUTRINO PHYSICS: A FEW EPISODES

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INTRODUCTION

On the occasion of the 70-th birthday of Edoardo Amaldi, about two years ago, I was invited to give a review talk on Neutrino Physics at an International Assembly of physicists, the major part of which was certainly not composed of neutrino physicists. Then the task was much simpler than today, since you are all professional "neutrinists". Notice that I have only 30 minutes at my disposition (instead of 2 hours at the Amaldi Conference). I must avoid the danger of being trivial by telling you the a,b,c of your own work. A way out of this difficulty, maybe, is to give a few recollections of such developments in neutrino physica which either are curious and at the same time very important (Pauli, Fermi) or about which I happen to be well informed for various reasons. Thus my talk will be entirely subjective (at a variance with the one I gave at the Amaldi celebration) and will be mainly dedicated to the young generation of neutrino investigators, who are well informed about today and yesterday developments, but not so well about old ones. I shall not talk about today problems, of course, since you are all here to discuss them during almost a week. By the way, most of you are used to think in terms of 10^5 - 10^6 neutrino events and forgot, if you knew it, that 16 years after the Pauli neutrino hypothesis (1930) neutrinos were still considered as undetectable particles, and, as you heard today, they were first revealed in the free state only 25 years after they had been invented.

Neutrino physics is almost a synonym of weak interaction physics, but there is a difference. I took such a difference into account, but not always.

In order to decrease the subjective character of my talk, I shall present a Table of events in neutrino physics. Of course this Table also is not objective. In the Table events are mentioned which either had a deciding meaning or initiated a large quantity of investigations. Of course, it was impossible to list all of them, even if their significance is greater than that of the investigation which initiated them. Two words more on the Table. I prepared it, at beginning,by memory, that is not consulting any literature. When eventually it became necessary to precise all the thing, I lost lots of time, but 95% of the original events remained and very few were added. I beg your pardon for deformations and omissions: the Table reflects the way by which neutrino physics has been influencing me. The Table is divided into four parts, with a rather loose periodization. First - from the discovery of radioactivity to the neutrino hypothesis, the Fermi beta decay theory and the detection of antineutrinos in the free state. Second - from the observation of weak processes other than the beta decay to the discovery of parity non-conservation in weak processes, the V-A universal theory and the observation of PC violation. Third - from the birth of high energy neutrino physics and the discovery of two neutrinos to the discovery of neutral currents, of the tau leptons, the weak decays of charmed particles and the theory of electroweak interactions. Fourth - neutrino in astrophysics, astronomy and cosmology.

For some reasons I started to prepare the literature for the fourth part. Later on I reduced drastically all the literature with the exception of the fourth part of the Table. Thus the literature has an accidental character. The reason is that I did not wish to prepare a sort of contents of the Proceedings of various International Conferences. One may find the necessary information just in such Proceedings.

An inspection of the Table indicates an amazingly fast growth of neutrino physics, which became a definitely quantitative science, healthy and powerful, and yet with lots of room for qualitative surprises.

Table

I

From the discovery of radioactivity to the neutrino hypothesis, the Fermi beta decay theory and the detection of (anti)neutrinos in the free state.

Year	Event	Authors and/or ref.
1	2	3
1896	Discovery of radioactivity	Becquerel
1899	Discovery of beta rays	Rutherford
1908	Counters (Geiger and proportional) capable of detecting single charged particles.	Geiger, Rutherford, Müller
1912	Cloud chamber	Wilson
1914	The continuous beta spectrum	Chadwick
1925	Nuclear photoemulsions	Misovsky
1927	Measurement of the heat released by beta rays	Ellis, Wooster
1927	Quantum theory of radiation	Dirac
1928	Relativistic equation of spin 1/2 particles	Dirac
1929	Two component theory of massless fermions	Weil
1930	The neutrino is invented	Pauli[1,2]
1932	The discovery of the positron	Anderson
1932	The discovery of the neutron	Chadwick
1932-1933	The nucleus is made up of nucleons	Ivanenko, Heisenberg, Majorana
1933	Theory of beta decay	Fermi
1934	Artificial radioactivity	Curie, Joliot
1934	Positron emission in beta decay	Curie, Joliot
1934	First discussion of the inverse beta decay	Bethe, Peierls
1935	Meson theory of nuclear forces	Yukawa
1935	Nucleus recoil in beta decay	Leipunsky[3]
1935	First mention of the double beta decay	Geppert-Maier[4]
1936	Far-reaching consequences of the fact that the Fermi constant is not dimensionless	Heisenberg
1936	Kurie plot	Kurie, Richards, Paxton

1	2	3
1936	Gamow-Teller selection rules	Gamow, Teller
1937	Neutrino Majorana	Majorana
1937	Nuclear orbital electron capture	Alvarez
1938	Discovery of the muon	Anderson, Neddermeyer
1939	Diffusion chamber	Langsdorf
1942	First nuclear reactor	Fermi et al.
1944	The principle of phase stability. Few years later the era is beginning of experiments performed on new types of powerful accelerators	Veksler; Macmillan
1945-1959	Christal counters and semiconductors detectors	Van Heerdin; McKay; McKenzie, Bronlay
1946	Proposal to detect low energy neutrinos with radiochemical methods	Pontecorvo
1947	The scintillation counter	Kallman
1949	Upper limit of the ν_e mass from ^3H decay	/5/
1950	Čerenkov counter	Jelley
1952	Bubble chamber	Glaser
1953	Conception of lepton charge	Marx; Zeldovich; Konopinski; Mahmoud
1953-1956	First observation of free (anti)neutrinos from a reactor	Reines, Cowan
1956	The reaction $\nu_e + {}^{37}Cl \rightarrow {}^{37}A + e^-$ is not observed $(\nu_e \neq \bar{\nu}_e)$	Davis

II

From the observation of weak processes other than the beta decay to the discovery of parity non-conservation in weak processes, the V-A universal theory and the observation of PC violation

1	2	3
1941	Direct proof of the muon radioactivity and direct measurement of its mean life (cosmic ray experiment)	Rasetti
1947	The muon is not a hadron (cosmic ray experiment)	Conversi; Pancini; Piccioni
1947	Discovery of the pion and of the $\pi - \mu$ decay (cosmic ray experim.)	Lattes, Occhialini, Powell
1947-1949	Deep analogy of various four fermion interactions and the conception of weak processes.	ref./8/
1947	Discovery of strange particles in cosmic rays	Rochester, Butler; Leprince-Ringuet
1948	Absence of the process $\mu \rightarrow e\gamma$ (cosmic ray experiment)	Hincks, Pontecorvo/7/; Sard, Althaus
1948	Observation of artificial pions; after this discovery very accurate measurements of the pion and muon masses, of their mean lives and of the energy of their charged decay products have been performed and are being performed. Similarly quantitative investigations of the strange particle properties have been performed.	Gardner, Lattes
1948-1949	Discovery of the neutron radioactivity	Snell, Miller; Robson

1	2	3
1949	In the muon decay 3 particles are emitted, the charged one being an electron: $\mu \to e + \nu + \nu'$ (cosmic ray experiments)	Hinks, Pontecorvo; Steinberger; Jdanov; Anderson et al.
1950	The Michel parameter	Michel
1950	Strong focusing in accelerators	Christophilos et al.
1952	"The dusturbing possibility remains that C and P are both only approximate and CP is the only exact symmetry law".	Wick, Wightman, Wigner /8/
1953-1954	Hadron isotopic multiplets. Strangeness	Gell-Mann, Nikishima
1953	The dual properties of neutral kaons	Gell-Mann, Pais
1954	The Yang-Mills fields	Yang, Mills
1954	Teorema CPT	Luders; Pauli
1955	First observation of antiprotons	Chamberlain, Segré
1955	Conservation of the vector weak current	Gerstein, Zeldovich
1955-1956	The $\theta-\tau$ paradox (parity non-conservation in the decay of strange particles)	Whitehead et al.; Barkas et al.; Dalitz et al.; Harris et al.; Fitch et al.
1956	Discovery of the long-live neutral kaon	Landè et al.
1956	Is parity conserved in weak interactions?	Lee, Yang
1956-1957	PC invariance	Landau; Lee, Yang
1957	P and C are violated in the ^{60}Co decay	Wu et al.
1957	P and C are violated in the $\pi-\mu$ and $\mu-e$ decays	Garwin, Lederman, Weinrich
1957	First mention of the unification of weak and electromagnetic interactions	Schwinger
1957	Longitudinal neutrino	Landau; Salam; Lee, Yang
1957	Observation of the longitudinal polarization of beta particles	Frauenfelder et al.; Alichanov et al.; Nikitin et al.
1957	The V-A universal weak interaction	Gell-Mann, Feynman; Marschak, Sudershan
1957	Electron-neutrino angular correlation in beta decay (^{35}A, ^{6}He) finally found in agreement with the V-A theory	Herrmansfelt et al.
1958	The $\pi \to e\nu$ process finally observed with a probability in agreement with the V-A theory	Fazzini et al.; Schwartz, Steinberger et al.
1958	Neutrino oscillations?	Pontecorvo
1958	Ionization calorimeter	Grigorov, Murzin et al.
1958	Unitary symmetry and weak interaction	Kobzarev, Okun
1958-1963	Theory of Cabibbo	Gell-Mann; Levy; Cabibbo
1958	The role of strong interactions in weak processes	Goldberger, Treiman
1959	"Kiev symmetry", that is "prequark" lepton-hadron symmetry	Gamba, Marschak, Okubo

1	2	3
1962	Observation and investigation of the reaction $\mu^- + {}^3He \rightarrow {}^3H + \nu_\mu$.	Falomkin et al.
1962	Observation and investigation of the reaction $\mu^- + p \rightarrow n + \nu_\mu$ in hydrogen	Hildebrand
1962-1963	Observation of the decay $\pi^+ \rightarrow \pi^0 + e^+ + \nu_e$ with a probability in agreement with CVC expectations	Dunaytzev et al., Depommier et al.
1963	In an experiment suggested by Gell-Mann CVC is confirmed in ${}^{12}N$ and ${}^{12}B$ decays	Lee, Mo, Wu
1964	PC violation ($K^0_L \rightarrow 2\pi$)	Christenson et al.
1964	Superweak interactions?	Wolfenstein
1967	Charge asymmetry in the lepton decays of K^0_L	Dorfan et al., Bennet et al.

III

From the birth of high energy neutrino physics and the discovery of two neutrino types to the discovery of neutral currents, of the tau leptons, the weak decays of charmed particles and the theory of electro-weak interactions

1	2	3
1959-1960	High energy neutrinos: a practical proposal which is opening a new field in weak interaction physics	Pontecorvo, Ryndin; Schwartz; Markov
1959	Spark chamber	Fukuni, Miyamoto
1959-1974	Theoretical discussion of parity non-conservation in atoms and in electron-nucleon interaction.	Zeldovich, Bouchiat

1	2	3
1961	Theory of electro-weak interactions	Glashow
1962	$\nu_e \neq \nu_\mu$ (spark chamber experiment)	Brookhaven, Danby et al.
1963	Magnetic "horn"	Van der Meer
1963	Combination of photoemulsions with other techniques for localizing the interaction position	Dvoretsky et al.
1963	Localization of neutrino interactions in emulsions with the help of spark chambers	Burhop et al.
1963-1964	Streamer chamber	Chikovani et al., Dolgoshein et al.
1963-1964	First neutrino experiments in which a bubble chamber is used	Cern, Block et al.
1964-1967	Weak nuclear forces	Abov et al., Lobashev et al.
1964	The fractional charge quarks (u, d, s)	Gell-Mann; Zweig
1964	The mechanism by which vector mesons acquire finite masses through spontaneous symmetry breaking	Higgs
1964	$\nu_\mu \neq \bar{\nu}_\mu$	Cern, Bernardini et al.
1963-1964	Theoretical introduction of charm	Maki, Nakagawa et al.; Bjorken, Glashow; Vladimirsky, Okun
1964	Every quark has three colours	Greenberg
1965	Integral charge triplet quarks	Bogoliubov, Struminsky, Tavkhelidze; Nan, Nambu

1	2	3
1965	Because of inelastic channels the total $\nu - N$ cross section probably will increase with energy in spite of the nucleon form factor, which limits the grow of the "elastic" $\nu - N$ cross section	Markov
1967-1972	Unified gauge model of electroweak interactions	Salam, Weinberg
1967	Quantization of massless Yang-Mills fields	Fadeev, Popov; De Witt
1967	Neutrino oscillations?	Pontecorvo, Gribov, Bilenky
1968	Proportional and drift chambers	Charpak et al.
1969	Scaling	Bjorken
1969	The parton model	Feynman
1971	Quantization of massive Yang-Mills fields	G't Hooft
1971	Bubble chamber Gargamelle (second generation of neutrino experiments)	CERN
1971	The idea of using a target-calorimeter in neutrino experiments (second generation of electronics neutrino experiments)	Rubbia et al.
1972	What neutrinos can tell us about partons	Feynman
1972	GIM mechanism: the fourth quark is necessary to make neutral currents symmetrical	Glashow, Illiopulos, Maiani
1972-1980	Total ν_μ and $\bar{\nu}_\mu$ cross sections on nucleons are increasing linearly with energy	CERN, Gargamelle and later other facilities
1972-1980	The Quark-parton model is confirmed by measurements of ν_μ and $\bar{\nu}_\mu$ charged current events	CERN, Gargamelle, and later other facilities
1973-1980	Observation of neutral currents in the process $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$	CERN, Gargamelle and later other facilities
1973	Observation of neutral currents in muonless events $\nu_\mu + N \to \nu_\mu + \ldots$	CERN, Gargamelle, Fermilab, HPWF; and later other facilities
1973-1974	Nucleon decay?	Pati, Salam; Giorgi, Glashow
1974	J/ψ particle	Ting et al.; Richter et al.
1975	The intermediate boson mass is < 17 GeV	Batavia, CITF
1975	Detailed proposal to detect "direct" neutrinos to study the production of charmed particles by nucleons	Pontecorvo
1975	The first charmed baryon is produced by neutrinos in the Brookhaven hydrogen bubble chamber	Cassoli et al.
1975	Pairs $\mu^+\mu^-$ produced in ν_μ and $\bar{\nu}_\mu$ events demonstrate the production of charmed particles by neutrinos	Fermilab, HWPF
1975	First observation of tau lepton	SPEAR, Pearl et al.
1976	The ν_e mass is < 35 eV	ITEP, Tret'yakov et al. /6/

1	2	3
1976	Processes $\nu_\mu + Z \to \mu^- + e^+ + \dots$ and $\bar{\nu}_\mu + Z \to \mu^+ + e^- + \dots$ demonstrate charmed particle production (H-Ne Fermilab large bubble chamber and CERN, Gargamelle)	Fermilab, Berkeley-CERN, Haway-Wisconsin; Aachen-Bruxelles-CERN-Ecole-Polytechnique Milano-Orsay London; Fermilab, ITEP-Michigan Serpukhov
1976	Observation of $\bar{\nu}_e e$ scattering (reactor experiment)	Reines, Gurr, Sobel
1976	Observation of elastic $\nu_\mu p$ and $\bar{\nu}_\mu p$ scattering and of parity violation in the weak hadron neutral current	Brookhaven, Harvard-Pennsylvania Wisconsin; Columbia-Illinois-Rockfeller
1977	Practical applications of detecting $\bar{\nu}_e$ (measurements of power, Pu accumulation) in reactor plants.	Mikaelyan et al.
1977	Discovery of the upsilon meson, probably a bound state ($b\bar{b}$) of bottom quarks of charge $\lvert 1/3 \rvert$	Fermilab, Lederman et al. Columbia-Fermilab-Stony-Brook
1977	Soon after the 400 GeV proton beam was available, a third generation of refined and good statistics high energy neutrino experiments starts at CERN	CDHS, Beps and later CHARM
1977-1980	"Beam Dump" experiments	Serpukhov, IHEP-ITEP; CERN, Aachen-Bonn-CERN-London-Oxford-Saclay (Beps) CERN, Gargamelle; CERN, CDHS; CERN, CHARM
1978	Parity non-conservation in atoms, in agreement with the Weinberg-Salam model	Barkov, Zolotarev
1978	Polarized electron scattering on deuterium conformes the Weinberg-Salam model and yields a value of $\sin^2 \theta_W$ in agreement with the results of the best neutrino experiments CDHS and CHARM	SLAC. Prescott et al.
1978	The ν_μ mass is < 0.57 MeV	SIN; Frosch et al.
1978	Some τ and ν_τ important properties are established: $m_\tau = 1782^{+2}_{-7}$; $m_{\nu_\tau} \leq 250$ MeV; V-A variant of τ decay	SPEAR, Kirkby et al.; Feldman et al.
1979	The polarization of muons produced by the interaction of neutrinos is found to agree with V-A expectations	CERN, CHARM
1979	Observation and investigation of the reactions $\bar{\nu}_e + d \to \bar{\nu}_e + n + p$; $\bar{\nu}_e + d \to e^+ + n + n$ (reactor experiment)	Irvine group, Pasierb et al.
1979	When meson factory π^+ are stopped in matter, ($\pi^+ \to \mu^+ + \nu_\mu$; $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$) the reaction $\nu_e + d \to e^- + p + p$ is observed, but not the reaction $\bar{\nu}_e + p \to n + e^+$, that is the decay $\mu^+ \to e^+ + \bar{\nu}_e + \nu_\mu$ is forbidden (no multiplicative lepton number)	Los Alamos, Burman et al.
1979	The mean life of charmed particles produced by neutrino interactions in nuclear emulsions or bubble chambers is measured and found to agree with theoretical expectations (few times 10^{-13} sec)	CERN, Collab., Wa 17; Fermilab, Berkeley-Batavia-Haway-Seattle-Wisconsin; Brookhaven, Brookhaven-Columbia

Much relevant work, which I was not able to quote, has been done and is being done at various Institutes. Below some data about neutrino beams and neutrino detectors are summarized for the benefit of "non-professional" neutrino physicists.

High energy neutrino beam facilities

Accelerator	Proton energy (GeV)	Decay length (m)	Muon filter (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
IHEP	70	140	62 (Fe)	2-30
FNAL	300-400	340	1000 (Earth+Fe)	10-200
CERN SPS	400	300	400 (Fe)	10-200

Large bubble chambers

Bubble chamber	Filling	Useful volume (m^3)	Weight (tons)
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, IHEP (USSR)	CF_3Br	4.5	7
BEPS, CERN	H_2, D_2, Ne	20-25	

Electronic detectors of neutrinos

Location	Collaboration	Useful target weight (tons)
CERN	Aachen-Padova (AP)	20
	CERN-Dortmund-Heidelberg-Saclay (CDHS)	900
	CERN-Hamburg-Amsterdam-Rome-Moscow (CHARM)	100
Brookhaven National Lab.	Harvard-Pennsylvania-Wisconsin (H.P.W.)	30
	Columbia-Illinois-Rockfeller (CIR)	8
IHEP, Serpukhov	ITEP-IHEP (S.S.)	30
FNAL	Harvard-Pennsylvania-Wisconsin-Fermilab (HPWF)	20
	California Inst. Technology, Fermilab (CITF)	100

(The most advanced detectors are CDHS and CHARM).

IV

Neutrino in astrophysics, astronomy and cosmology

1	2	3
1939	Emission of neutrinos in thermonuclear reactions in the Sun and other stars	Bethe [9]
1941	Supernovaes and "Urka" processes	Gamow, Schonberg [10]
1946	Radiochemical methods for detecting neutrinos, for example, the Cl-A method used in Solar neutrino astronomy	Pontecorvo [11]

1	2	3
1946	The big-bang theory	Gamow /12/
1958	B^8 as a source of relatively high energy solar neutrinos	Fowler /13/
1959	Neutrino emission from hot stars due to the universal Fermi interaction (the $\nu_e + e \to \nu_e + e$ process)	Pontecorvo /14/
1960	The importance for elementary particle physics and astrophysics of performing experiments at great depths underground and under water	Markov /15/ Greisen /16/
1961	Phenomenological considerations on the possible existence of a "neutrino sea"	Pontecorvo, Smorodinsky /17/
1961	Upper limits imposed by cosmological considerations on the amount of invisible energy	Zeldovich, Smorodinsky /18/
1962	Possible emission of pairs $\nu\bar{\nu}$ due to hypothetical neutral currents	Pontecorvo /19/
1963	A large detector of (atmospheric) cosmic ray neutrinos located at depth 8700 m.w.e. in a South Africa mine (8 years of measurements, ~100 events)	Case Institute of Technology and University of California, Irvine, Reines et al. /20/
1964	Neutrino stars?	Markov
1965	Telescopes and magnetic spectrometers located at a depth 7500 m.w.e. in the Kolar Gold Fields in Southern India, aimed to detect atmospheric cosmic neutrinos (6 years measurements, ~20 events)	India-Japan collaboration, Krisnashvami et al.; Osborne et al. /21/
1965-1966	Neutrino processes and pair formation in massive stars and supernovaes	Fowler, Hoyle /22/ Colgate, White /23/

1	2	2
1965	Emission of detectable neutrinos ($E \geq 10$ MeV) in the collapse of cooled stars, i.e., in the process of neutronization: $e^- + {}^{Z}A \to \nu_e + {}^{Z-1}A$	Zeldovich /24/
1965	Proposal of an experiment aimed to detect neutrino from collapsing stars	Domogatsky /25/ Zatsepin
1965-1967	Discovery of the relict electromagnetic radiation, confirming the bing-hang theory and requiring the presence of a similar relict neutrino sea, with important implications for cosmological nucleosynthesis	Penzias, Wilson /26/ Dicke et al. /27/ Zeldovich, Novikov /28/ Weinberg /29/
1966	Upper limit on the ν_μ mass imposed by cosmological considerations	Gershtein Zeldovich /30/
1968-1967	The necessity of clearing up the question about lepton charge conservation and the number of neutrino types (neutrino oscillations) for the future of solar neutrino	/31,32,33/
1972	Expectations for the ${}^{37}Cl - {}^{37}A$ solar experiment based on solar standard models	Bahcall /34/
1975-1977	Cosmic sources of ultra-high energy neutrinos	Beresinsky /35/ Zatsepin
1977	A quantitative theory of Supernovaes, where neutrino heating ignites thermonuclear processes in carbon	Gershtein et al. /36/
1977	Scintillation telescope of the Institute of Nuclear Research placed at 800 m.w.e.	Chudakov et al. /37/

1	2	3
	in the Baksan Valley, having a total mass of 300 toms (3150 moduli)	
1977	Acustic wave detector of ultra-high energy neutrinos	Dolgoshein et al.[38] Sulak et al.[39]
1977	The importance of neutrinos emitted during the collapse of stars for the nucleosynthesis, especially for explaining the abundance of proton-rich nuclei	Domogatsky et al.[40]
1978	Definite detection of Solar neutrinos by the Cl-A method in an experiment which lasted more than 10 years	Davis et al.[41]
1978	Cherenkov H_2O detector (~500 tons) of star collapse neutrinos places underground in S.Dakota, Ohio and under the Mont Blanc	Landé et al.[42]
1978	INR scintillation detector of star collapse neutrinos (100 tons) placed in a salt mine at Artyomovsk (600 m.w.e.)	Zatsepin et al.[43]
1980	Scintillation detectors of star collapse neutrinos (60 moduli each 2 m^3) located under the Mont Blanc	Collaboration INR-Torino
1980	Deep Under Seas Muon and Neutrino Detector (one cubic kilometer optical-acoustic H_2O detector)	See for ex. Learned[44]

PAULI

It is difficult to find a case where the word "intuition" characterises a human achievement better than in the case of the neutrino invention by Pauli.

First, 50 years ago there were known only two "elementary" particles, the electron and the proton, and the very idea that for the understanding of things the existence of a new particle becomes imperative was in itself a revolutionary conception. What a difference from the present day situation, when at the slightest provocation lots of people are ready to invent any number of particles!

Second, the invented particle, the neutrino, should have quite exotic properties, especially an enormous penetrating power. True, Pauli at the beginning did not recognize fully such unescapable implications of his idea and modestly conceeded that the neutrino may have a penetrating power about equal or ten times larger than a γ quantum. Incidentally, a dimensional thermodynamical argument, showing that neutrinos of energy ~1 MeV or wave length λ must have an astronomically large mean free path, let's say equal to a thickness of water milliard of times greater than the Earth-Sun distance, was first given by Bethe and Peierls[45] who considered the two inverse processes (I am using modern notations): $z \to (z+1) + e^- + \bar{\nu}_e$ (this is a beta process taking place with a characteristic time T) and the inverse reaction $\bar{\nu}_e + (z+1) \to z + e^+$, characterized at the mentioned neutrino energy by a cross section σ:

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

The argument, which today is self-evident (almost all good arguments look obvious "a posteriori") made a deep impression upon me. I did not forget it many years later, when I suggested how free neutrino experiments might be performed with the help of reactors[11].

Third, the neutrino, because of its fantastic penetration, appeared first as a particle which, as it were, cannot be revealed in the free state, and on the existence of which you can judge only on the basis of the laws of energy and moment conservations, by detecting the nuclear recoils in the β decay, that is with the help of a method which today is quite currently used in searches for neutral particles - the so-called "missing mass" method. Experiments of this type were suggested by Pauli and the first of these was performed in Cambridge by Leipunski. Here I would like to underline that

50 years ago there was known only one process involving the neutrino, the β decay of heavy nuclei, which is a 3 particle process. Extremely important experiments of Ellis and others showed that the average energy (measured in a calorimeter) of the beta rays is equal to the average energy of the β spectrum, measured in a magnetic spectrometer. This clue, together with the notion that there is a maximum energy of β rays was certainly not missed by Pauli. All the other processes in which, as we know now, neutrino take part, were not known at the time. Among these several two particle decays from charged particles stopping in a track detector ($\pi^+ \to \mu^+ + \nu_\mu$; $\mu^- + {}^3\mathrm{He} \to {}^3\mathrm{H} + \nu_\mu$...) leave behind beautiful signatures, since the emitted charged particle has always the same momentum, cf course equal to that of the invisible neutrino. Examples of these processes are well known to everybody present here. If in the time previous to the Pauli invention such a two particle events had been discovered, there would not have been the need of Pauli genious to invent the neutrino. However, I would like to mention here that, at the time, Bohr thought that the continuous β spectrum might arise from energy non-conservation in individual processes, so that, strictly speaking, in order to solve the dilemma neutrino versus energy non-conservation, one may not be allowed in principle to make use of conservation laws.

Some more words on the Pauli invention, about which he wrote himself a few tens of years after his famous proposal, which, incidentally, was never published in a scientific periodical. Maybe not all of you know that the first idea on the existence of the neutrino appeared in a letter [1] to a group of specialists in radioactivity, who were to meet in Tübingen, the letter starting with these words: "Dear radioactive ladies and gentlemen". At this meeting Pauli was not present because he was expecting much more from a ball which he wished to attend in Zürich, the night of December 6, 1930. But in that letter there were not only jokes. There are two ideas that only a man of great intuition could have. These ideas I will formulate in the today and the Pauli terminology.

1) In the nuclei there must exist electrically neutral particles, neutrons (Pauli also called them neutrons) having spin 1/2.

2) In the β decay together with the electron there must be emitted a neutral particle, the neutrino (Pauli called it neutron), so that the total energy of the electron, neutrino and recoil nucleus is discrete, as it should be.

Thus Pauli "invented" two particles at the same time and both were very necessary (keep in mind, among other things * the so-called nitrogen catastrophe, that is the proof given in the classical spectroscopic investigations of Rasetti, that nuclei ${}^{14}\mathrm{N}$ obey the Bose statistics, so that they can hardly consist of protons and electrons only). Pauli for a time thought he had invented only one particle, because mistakenly he identified them. Soon, however, he understood his error, namely, in the first official publication [2] about the neutrino (so it was called by Fermi) at the 1933 Solvay Congress. The subsequent colossal step was done by Fermi.

FERMI

Fermi got acquainted with Pauli hypothesis in 1931 at an International Conference of Nuclear Physics, where the β decay problem was discussed. There Bohr talked in favour of energy non-conservation. Fermi was quite impressed by the Pauli particle, which he started to call "neutrino". At the 1933 Solvay Conference [2] for the first time in a discussion, which appeared in the press, Pauli told about his idea. Fermi evidently was already thinking deeply about the problem: his famous paper "A Tentative Theory of β Decay" [46] appeared only 2 months after the end of the Solvay Congress. This is a quantitative theory, which had a great influence on the development of physics. Without any doubt the idea on the existence of the neutrino would have remained a vague notion without Fermi's contribution. This theory amazingly resisted almost without change until now and underwent only relatively small, although quite important and numerous additions. I feel quite confident that, had been Fermi alive, he would have made himself at least most of the additions, under the pressure of new experimental facts, about which I will talk later.

I would like now to say some curious facts about the appearing of the theory, facts, which I have seen with my eyes, since in that period I was working in Rome.

1) The Journal "Nature" refused the paper of Fermi, because it appeared too abstract to be of interest for the readers. I am sure the editor has regretted such episode for all his life.

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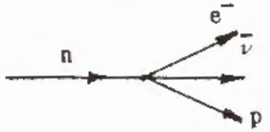
* Details on the theoretical thinking (Rutherford, Pauli and especially Majorana) about the neutron before its experimental discovery by Chadwick are most interesting, but I have not the possibility to discuss them here.

2) The second curious thing has to do with the difficulties Fermi encountered. Such difficulties were not mathematical, but physical. The necessary mathematics, the secondary quantization, he learned quickly, but the most serious difficulty was to recognize the fact that the electron and the neutrino are created when a neutron transforms into a proton. Of course, this is a thing that every student knows today: elementary particle interactions are explained by the exchange of elementary particles. This is quantum field theory and is an unescapable consequence of the quantum theory and of the theory of relativity. Particles are created and destroyed. This was the difficult point for Fermi. Pauli, in spite of its pioneer work in quantum electrodynamics, did not formulate clearly this point, and if you read the famous Fermi article on β decay, you see how he worked making an analogy with the Dirac quantum theory of radiation (photons are created and destroyed!) and how by analogy he selected the V variant of the β decay.

I still remember his words: when the excited Na atom emits the 5890 Å line, the photon is not sitting in the atom (it is created), similarly the electron and the neutrino are created when a neutron is changing into a proton.

At a variance with an interaction at a distance $e\bar{\psi}_p\gamma_\mu A_\mu$, as in the case of the electromagnetic interaction (through the exchange of a photon) Fermi assumed that the two currents, the heavy particle (n, p) and the light particle (e, ν) currents have a contact interaction

$$k\bar{\psi}_p\gamma_\mu\psi_n\bar{\psi}_e\gamma_\mu\psi_\nu$$



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 the Fermi constant, $\hbar=c=1$), $\bar{\psi}_p, \psi_n$ are the creation operator of the proton and the destruction operator of the neutron, etc. Fermi assumed that weak currents, as we call them now, are four-vectors, as in electrodynamics. At the beginning, Fermi felt that the nucleon weak current $\bar{\psi}_p\gamma_\mu\psi_n$ is the analogous of the electromagnetic current $\bar{\psi}_p\gamma_\mu\psi_p$ and that the lepton weak current $\bar{\psi}_e\gamma_\mu\psi_\nu$ is the analogous of the electromagnetic field. However, in his formulation the nucleon and lepton currents, as a matter of fact, are on identical foot. Thus Fermi created its perfect building starting from a few experimental results on the beta decay of heavy nuclei, especially RaE and from an analogy with Dirac theory of radiation.

POST FERMI

I would like to underline here that our knowledge since that time has increased tremendously; however (almost) all the new things fit wonderfully into the Fermi picture. The new things you may find in the Table, especially in parts II and III.

I shall briefly summarize some of these new things:

1) Neutrinos are not only emitted in beta decay processes. There are numerous processes in which the neutrinos take part: decays of non-strange particles, decays of strange particles, decays of charmed particles, inverse of these processes induced by high energy neutrino beams, decays of charged leptons (μ and τ), deep inelastic scattering of neutrinos by nucleons, scattering of neutrinos by electrons and nucleons.

2) Even a small part of these facts was sufficient to suggest that the Fermi interaction describing the beta decay process is a special case of four-fermion interactions having about the same strength. This is how there arose the conception of weak interactions

3) There exist at least 3 types of leptons e, μ, τ and "their" neutrinos ν_e, ν_μ, ν_τ two of which have been observed through their interactions in the free state with the help of reactors $(\bar{\nu}_e)$/47/, the Sun (ν_e)/41/, and accelerators $(\nu_\mu, \bar{\nu}_\mu)$/48/.

4) In weak processes neither parity P nor charge conjugation C are conserved although the laws of nature are (almost) invariant with respect to the combined inversion PC, which changes simultaneously the signs of coordinates and charges. Non conservation of parity implies longitudinal polarization of particles and thus there arose the theory of two component neutrino of Landau, Lee and Yang and Salam, which is an old theory of Weil, made plausible by parity non-conservation. A good model of the neutrino according to this theory is a screw. Actually it was shown experimentally by Goldhaber that neutrinos are left-handed. Anti-neutrinos are right-handed. Thus we have two states only and not four, as for an actual screw: screw left-handed, screw right-handed, antiscrew left-handed, antiscrew ringh-handed. Now the importance of the longitudinal neutrino is that such neutrino gives us the prototype of the behaviour of all other (not massless) fermions, under weak interaction. A simple mnemonic rule is that, under weak interaction, all fermions are left-handed, all anti-fermions are right-handed. This has been incorporated in the famous universal weak interaction V-A theory of Feynman and

Gell-Mann, Marschak and Sudershan. As we saw, in analogy with electrodynamics, the weak interaction involves vector operators working on the wave-functions of particles. But there are two amplitudes - V, the original Fermi one, which has the spatial transformation properties of a polar vector (that is, it changes sign under inversion of the space coordinates), while the other, A, has those of an axial vector (it does not change sign). Namely the coexistence of V and A means non-conservation of parity. Thus the Fermi weak current, which was originally a vector one, in fact became the sum of a vector and axial vector (the last one being constructed with the help of the matrix $\gamma_\mu \gamma_5$, where $\gamma_5 = i\gamma_0\gamma_1\gamma_2\gamma_3$). Now I would like to come back to Fermi and to think for a moment: what might have happened if, in 1954, the fate had granted to him few years more? I believe that probably he would have invented the two-component neutrino, but I am not certain about it. What I am certain about is that Fermi, after either he or Landau, Salam, Lee and Yang had discovered the two-component nature of the neutrino, would have created the V-A theory. Not only he had started in 1933 the all business, but in the middle fifties he, a great theoretician and experimentator, better than anybody else would have recognized that some experiments, those experiments which made difficult the formulation of the Universal theory, were wrong.

5) Hadrons are mixed, that is in the weak interaction there take part coherent mixtures of hadrons. Using quark notations, the hadron charged current is $\bar{u}(d\cos\theta + s\sin\theta) + \bar{c}(-d\sin\theta + s\sin\theta) + \dots$ where θ is the Cabibbo angle ~15°, $\bar{u}$ is the creation operator of the u quark, d is the destruction operator of the d quark, etc. Thus the weak interaction Lagrangian is $L_w = \frac{G}{\sqrt{2}} J_w J_w^+$, where

$$J_w = \bar{e}\nu_e + \bar{\mu}\nu_\mu + \bar{\tau}\nu_\tau + \dots + \bar{u}(d\cos\theta + s\sin\theta) + \bar{c}(-d\sin\theta + s\cos\theta) + \dots$$

$$J_w^+ = \bar{\nu}_e e + \bar{\nu}_\mu \mu + \dots \quad + (\bar{d}\cos\theta + \bar{s}\sin\theta)u + (-\bar{d}\sin\theta + \bar{s}\cos\theta)c + \dots$$

and every member is a sum of V and A of the type $\bar{e}\gamma_\mu(1+\gamma_5)\nu_e$, etc. Once more this Lagrangian is a generalization of the Fermi one with essential, but very natural, additions, which take into account post-Fermi experimental data. It accounts wonderfully for all the data concerning charged currents, of which the β-decay a la Fermi is the first example.

Incidentally, it is quite likely that not only hadrons but also leptons are mixed (with important implications relating to neutrino oscillations). As I already promised, however, I am not going to talk about things which will be discussed in detail at our Conference.

6) Now I should mention the most important discovery of neutral currents, made at CERN and confirmed at the Fermi Lab. I must say that neutral currents had been discussed as possible and even likely processes a long time before a real theory - the Glashow-Salam-Weinberg theory of electro-weak interactions - was proposed. As you know, largely as a stimulus of such a theory neutral currents were discovered experimentally. I am not going into that now, first, because it is much more interesting for you to read the Nobel talks of Glashow, Salam and Weinberg and, second, because work on neutral currents will keep you very busy all this week. Incidentally, together with the discovery of neutral currents, I think that the most important work in neutrino physics is the marvelous investigation of neutral currents of the CDHS group. But I must say that phenomenologically neutral currents of the symmetrical type ($\bar{e}e$, $\bar{\nu}\nu$, $\bar{p}p$ ....) had been seriously discussed by many people, including Bludman. I have even discussed /19/ in 1962 some astrophysical consequences of such currents. The consideration of symmetrical neutral currents was very natural. Because of the overwhelming competition of electromagnetism nobody could prove that they are not present. But how about the absence of asymmetrical neutral currents $\bar{\mu}e$, $\bar{s}u$...? I simply thought that they are ugly and the symmetrical ones beautiful. GIM had not yet been invented. I would like to conclude with two remarks:

a) The very first experiment /49/ on high energy neutrino physics was designed to detect neutral currents, true, at a level 10^4 times smaller than the expected charged currents. This was all we could do with the low intensity accelerator available to us, our hope being on an anomalous $\nu_\mu - N$ interaction /50/.

b) In the course of many years neutral currents at the proper level have been looked for (and not found!) for example at CERN, of course before the Glashow, Salam, Weinberg strategy became popular.

THE ^{37}Cl-^{37}A METHOD

I would like now to give a subjective account of a few pages in the development of neutrino physics, in which in some ways I was involved. In 1946 neutrinos were generally considered undetectable particles. Many respectable physicists were of the opinion that the very question about detecting free neutrinos was nonsense (not only because of temporary difficulties), just as nonsense is the question as to whether the pression in a vessel is or is not, say, less than 10^{-50} atmospheres. I remembed well the Bethe-Peierls argument/45/ and it occured to me at the time that the appearance of powerful nuclear reactors made free neutrino detecting a perfectly decent occupation. I was living in Canada then and was well acquainted with reactor physics. The NRX Canadian reactor, in the design of which I was taking part, was not working yet, but it was clear to me that under the very compact shield, where the cosmic ray soft component was considerably weakened, one might dispose of a neutrino flux $\sim 10^{12}$ cm^{-2} sec^{-1}. At the time, scintillators, which were so successfully used many years later by Cowan and Reines to detect free reactor antineutrinos, has not yet been invented. Well, it occurred to me that the problem could be solved by radiochemical methods, that is,by concentrating chemically the isotope resulting from the inverse beta process from a very large mass of matter irradiated by neutrinos. A careful inspection of the famous Seaborg table of artificial radioisotopes indicated a few possible target candidates, by far the best of which was a chlorine compound, the reaction at issue being:

$$\text{neutrino} + {}^{37}\text{Cl} \rightarrow {}^{37}\text{A} + e^{-} , \qquad (1)$$

where ^{37}A decays by K-capture with the emission of 2.8 keV X-rays. I wrote here "neutrino" and not $\bar{\nu}_e$, because at the time the question as to whether $\nu_e = \bar{\nu}_e$ was not clear, but to this point I shall come back later. Now there are lots of practical reasons why ^{37}Cl is so good and I shall not list them here. One of them, however, was not known to me "a priori" and was discovered by chance. In order to experiment on the future neutrino detector at Chalk River we were preparing in a conventional way ^{37}A, and putting it inside a detector which according to our intentions was supposed to be and in fact was, a Geiger-Müller counter. Well, once, looking at an oscilloscope connected to the counter, we saw plenty of pulses from ^{37}A about equal in amplitude at voltages on the counter much lower than the Geiger threshold, and discovered (independently of Curran et al. in Glashow) the high gas gain (up to 10^{6}) proportional regime. Now this was very important, of course, from the point of view of detecting neutrinos, since it permits to decrease the effective background of the counter. At the time there was a sort of dogma about proportional counters, i.e., that they cannot work at multiplication factors larger than ~100, which is true of course, if you have a large input ionization (alpha particles, etc.), but is absurd if you have an input ionization of a few ion pairs.

I discussed the ^{37}Cl-^{37}A method with Fermi in Chicago (1947?) and later at the Basel-Como conference in 1949 (including solar possibilities). Fermi was not at all enthusiast about neutrino applications of the method, but liked very much our proportional counters, with the help of which together with Hanna we first observed L-capture (in ^{37}A, 10 ion pairs)/51/ and measured the ^{3}H spectrum going quite down at the time with the upper limit of the neutrino mass/5/. In reprospect I understand very well Fermi's reaction. As I think that Segrè said, Don Quixote was not the hero of Fermi. He could not have sympathy for an experiment which, true, grace to the heroic efforts of R.Davis, terminate very brilliantly, but many many years after its conception/41,52/.

Now I am coming back to the question as to whether reactor antineutrinos may induce the reaction (1). Well, passing through Zürich sometimes between 1947 and 1948 I had lunch with Preiswerk and Pauli. I told Pauli about my plans with the ^{37}Cl-^{37}A method; he liked very much the general idea and remarked that it was not clear whether "reactor neutrinos" should definitely be effective in producing the reaction (1), but he thought that they probably would. Since that time the question became very clear to me and until 1950 I continued to think about it and to test low background proportional counters in that connection and in connection with solar problems. For example I remember that Camerini, who at the time was working in Bristol and was a great specialist in cosmic ray stars, helped me to calculate the cosmic ray background in various Cl-A experiments which I was planning to do. Anyway the effective background of my counters was sufficiently low to detect solar neutrinos/11/ through ^{37}A decay. Since 1950 I stopped experimenting on the problem,as there was no site deep underground enough in the USSR for a solar experiment (as you know, at the Elbrus neutrino observatory such a site will be available). However I kept thinking about counters and when I had the privilege to meet R.Davis at the first Neutrino Conference in Moscow (1968), I told him that measuring the form of the counter pulse should result in a considerable decrease of the effective background in its solar experiment. As I found out later from him at the ν'72 conference in Hungary it works really that way. But now I am going back about 15 years.

NEUTRINO OSCILLATIONS

You all know that R.Davis/52/ has shown in 1955 that reactor (anti)neutrinos cannot effectively produce ^{37}A from ^{37}Cl, that is $\nu_e \neq \bar{\nu}_e$. Now at the time I was told in a wrong way about such experiment. A delegation came to Moscow and someone (I do not remember who) told me that R.Davis got a positive signal in his experiment. Such result at the time seemed to me fantastic (and rightly so!). Wrong rumors sometimes are useful. I tried to find a way out and invented[53] neutrino oscillations of the type $\nu_e \rightleftarrows \bar{\nu}_e$. This was all wrong, and not only because the fact which needed explanation was not there, but also, as I found out later, because of different spiralities of ν_e and $\bar{\nu}_e$. Nevertheless, this wrong thinking was very useful to me ten years later, when the question about possible neutrino oscillations was investigated in a modern way from a theoretical point of view and with the aim to consider many possible experiments (reactor, accelerator, cosmic, solar neutrinos)[31-33]. Among other things, the number of neutrino types considered was ≥ 2. Now neutrino oscillations and the question about neutrino masses are very much "a la mode" from a theoretical as well as an experimental points of view, as one can see by an inspection of the programs of our Conference and of the "Rochester" conference of this year. Thus you will discuss here oscillations and neutrino masses at length and at the proper time. As Iago, I am saying: "Demand me nothing: what you know, you know: From this time forth I never will speak a word". However I wish to acknowledge the great benefit of the collaboration with I.Kobsarev, L.Okun and especially with V.Gribov and S.Bilenky.

HIGH ENERGY NEUTRINO PHYSICS

My story here is again very personal. I am goung to tell you how I came to propose experiments with high energy neutrinos from meson factories and from very high energy accelerators. At the Laboratory of Nuclear Problems of the JINR in 1958 a proton relativistic cyclotron was being designed with a beam energy 800 MeV and a beam current ~500 μA. This accelerator eventually was not built because of financial difficulties. In retrospect I think that non going ahead at the time with an accelerator having parameter similar to those of today meson factories was an error. Anyway at the beginning of 1959 I started to think about the experimental research program for such an accelerator. It occurred to me that a healthy and relatively cheap neutrino program could be accomplished by dumping the proton beam in a large Fe block, fulfilling at the same time the function of neutrino source and shield. I would say that the ideology of the LAMPF accelerator neutrino experiments

which have been initiated recently is very similar to that of various experiments planned 20 years before[54,55] for an accelerator which was not built. About one of them, which was intended to clear up the question as to whether $\nu_e \neq \nu_\mu$ I would like to say a few words.

I have to come back a long way (1947-1950). Several groups, among which J.Steinberger, E.Hincks and I, and others were investigating the (cosmic) muon decay. The result of the investigations was that the decaying muon emits 3 particles: one electron (this we found by measuring the electron bremstrahlung) and two neutral particles, which were called by various people in different ways: two neutrinos, neutrino and neutretto, ν and ν', etc. I am saying this to make clear that for people working on muons in the old times, the question about different types of neutrinos has always been present. True, later on many theoreticians forgot all about it, and some of them "invented" again the two neutrinos (for example M.Markov), but for people like Bernardini, Steinberger, Hincks and me... the two neutrino question was never forgotten. Not trivial, "a priori", was the question about how to perform the experiment, a thing which I was able to formulate clearly enough[54].

In 1959 another problem was of great importance; is the four-fermion interaction a contact interaction or is it due to the exchange of an intermediated boson? This question is still valid today, but now we have the Glashow, Salam, Weinberg theory, which predicts masses of intermediated mesons at about 100 GeV, whereas in 1959 the intermediated boson (without serious reasons) was supposed to have a mass of a few GeV. Obviously the intermediated boson could not be produced at meson factories and at the 1959 Kiev international conference Ryndin and I proposed to look for the boson making use of neutrino beams from very high energy accelerators[56]. The theoretical idea in the proposal was that in the cross section for the production by neutrinos of the intermediate boson at sufficiently high energies there will appear G instead of G^2. As you know, the question about intermediate bosons, which was very hot at high energy accelerators until about 1972, is not going to be solved anymore in neutrino experiments (as it seems). The question about two types of neutrinos has been solved at Brookhaven in a beautiful experiment[48].

AN ALTERNATIVE SCENARIO OF THE NEUTRINO PHYSICS DEVELOPMENT

Now I would like to present a scenario of the weak interaction physics development which did not take place but might actually have taken place. Since most of you are high energy neutrino physicists, such a scenario will get on your nerves. By the way, I shall act as the devil's advocate, since I am very much for high energy neutrino physics myself.

I know a great scientist, P.Kapitza, who thinks now that if an experiment is very expensive and/or cumbersome, it should not be done: with time the problem at issue will be solved in a simpler way. Well, suppose that in the early sixties the community of physicists had decided that neutrino experiments at very high energy accelerators are too expensive and cumbersome. The community, as it were, was then of the opinion that neutrino physics in a relatively cheap way should be done at meson factories, which were been built anyway and at nuclear reactors. Which would have been the results? Let us follow the lines indicated by the actual great achievements of high energy neutrino physics.

1) $\nu_e \neq \nu_\mu$. This result would have been obtained at meson factories, true, at least 10 years later. Incidentally, electron-positron collisions gave us the ν_τ .

2) The nucleon structure. Here the situation without high energy neutrino experiments would have been catastrophic. However do not forget about the information (true, different) from deep inelastic scattering of electrons and muons, which is not bad at all.

3) Neutral currents. They have been discussed by many people from a phenomenological point of view /57/ before the theory of electro-weak interactions, which clearly would have been created anyway, that is without high energy neutrino experiments. The parity non-conservation in atoms, predicted by Zeldovich /58/ (for example the optical activity of Bi vapour) has been observed in Novosibirsk /59/, in agreement with the theoretical expectation of Glashow-Salam-Weinberg. It is an experiment difficult and refined, but relatively cheap. The beautiful SLAC experiment /60/ on the scattering of polarized electrons by nucleons gives a very accurate value of $\sin^2\theta_w$. At reactors and meson factories neutrino experiments on neutral currents have been performed and are being planned. Of course the very accurate work at CERN on neutral currents and the values of $\sin^2\theta_w$ from CDHS (and now CHARM) would be lacking, and this would be quite serious.

4) Without high energy neutrinos the production of strange and charmed particles by neutrinos could not have been investigated. However we got most of our knowledge on the subject in hadron beam investigations and in electron-positron collisions.

5) The mean life of charmed particles. This is an important and recent result of high energy neutrino investigations /61/. However, I am convinced that with the help of other methods analogous results may be obtained.

Thus I shall summarise: what actually happened in high energy neutrino physics, is very expensive, but is much more informative than the consequences of my hypothetical scenario. But one should neither underestimate the importance of high energy neutrino physics nor overestimate it. This is not a note of pessimism but an appeal to avoid routine. Now high energy neutrino physics is a very healthy field of physics, in which quantitative measurements dominate. However in neutrino physics, one feels, there is still plenty of room for new qualitative results. Some new ideas concerning neutrino beams (tagged?), detectors, and problem formulations are needed. I think that neutrino oscillations and beam dump experiments are promising, but they are no more real news. Concerning beam dump neutrino experiments I would like to draw your attention to an amusing thing.

BEAM DUMP EXPERIMENTS

In the beam dump experiments which have been performed at Serpukhov and at CERN (by four groups), the production of charmed particles in proton nuclear collisions has been observed and investigated for the first time, the method consisting in the detection of prompt neutrinos from the lepton decay of charmed particles. Now this is a miracle, which you may appreciate by making analogies of the following type: when the beta decay of nuclei was first observed, you may imagine that Rutherford, instead of detecting electrons, observed neutrinos from a 10^9 curie source! or you may imagine that Lattes, Occhialini and Powell first observed the pion decay by designing and building a modern neutrino high energy facility (with a proton accelerator, the decay tunnel, the Fe shield and a multi-ton neutrino detector), instead of observing simply, as they did, the pion-decay muons.

CONCLUSIONS

What happened in neutrino physics the last years is a miracle. Everything, that is the Glashow-Salam-Weinberg theory of electro-weak interactions, looks perfectly O.K. It is too good. The appetite comes with eating and this means Grand Unification. But I do not believe that elementary particle physics will soon die of abundance of understanding and or lack of problems to be solved. Let us discuss now about unexpected things, since anyway about such things one does not talk seriously in a lecture entitled "Fifty Years of Neutrino Physics". But there are already more or less important things. One of them, finite neutrino masses (together with the instability of the proton) is in the head and in the mouth of everybody. Its implications - neutrino oscillations - are extremely informative (masses of neutrinos, number of them, and mixing angles), if something can be done, as it seems, in controllable experiments of various types (reactor, accelerator, cosmic, solar). It is not excluded* that the ν_e mass may be measured directly from the ^3H beta spectrum, although I am not sure that this can be done, just because of the fantastic, I would say acrobatic, difficulty of the experiment, which incidentally, is a relatively cheap one /5/.

Be as it may, finite neutrino masses not only would confirm modern theoretical thinking and give us very necessary parameters but would originate a revolution in cosmology, astrophysics and neutrino astronomy.

It is curious that today most popular types of search experiments - the proton radioactivity and neutrino oscillations - are not, in the main, high energy experiments.

I finished my talk. It is time to start working.

REFERENCES

1. Pauli: letter (4 December 1930) to a meeting of physicists, among which Geiger and Meitner, taking place in Tübingen. The letter was conserved by Meitner and its content was discussed since 1930. The letter was widely published only after many years. (See, for example: Brown. Phys.Today, September, 1978).
2. Pauli. "Septieme Conseil de Physique Solvay 1933", Gauthier-Villars, Paris, 1934.
3. For accurate measurements in the reaction $^{37}A + e^- \rightarrow {}^{37}Cl + \nu$ (K-capture) see: Rodeback, Allen. Phys.Rev., 1952, 86, p.466.

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* After this paper was written, a preprint was published in which a finite mass (between 14 and 46 eV within 90% confidence limits) was claimed for the neutrino emitted in the beta decay of ^3H : Lubimov, Nozik, Tretjakov, Kozik, ITEP 62, 1980.

4. See for reviews of the subject: Primakov and Rosen. Report on Progress in Physics, 1959, 22, p.121; Fiorini. Proc. of the ν'77 Conf., Ed. Nauka, Moscow, 1978. Neutrinoless double beta decay has not been observed and upper limits 10^{-3} - 10^{-4} for the lepton non-conserving relative amplitudes have been set for the double decays $^{48}Ca \rightarrow {}^{48}Ti$ (Bardin et al.), $^{76}Ge \rightarrow {}^{76}Se$ (Fiorini et al.), $^{82}Se \rightarrow {}^{82}Kr$ (Cleveland et al.), $^{130}Te \rightarrow {}^{130}Xe$ (Zdelenko et al.).
5. The first measurements of the ^3H beta spectrum were performed by means of proportional counters in 1949: Hanna, Pontecorvo. Phys.Rev., 1949, 75, p.983; Curran et al. Phil. Mag., 1949, 40, p.53. Then substantial improvements were obtained by using as a ^3H source a few molecule thick layer and a magnetic spectrometer. The last and best result is $m_{\nu_e} \leq 35$ eV (90% C.l.). (Tret'jakov et al., Proc. of the Int. Conf. on High Energy Phys., Tbilisi, 1976, vol. II, p.118). Less accurate measurements have been performed by implanting ^3H in a Si(Li) detector (Simpson, Proc. ν'79 Conf., vol.2, p.208).
6. Pontecorvo. Phys.Rev., 1947, 72, p.246; Puppi, Nuovo Cimento, 1948, 5, p.505; Klein, Nature, 1948, 161, p.897; Lee et al. Phys.Rev., 1949, 75, p.905; Tiomno, Wheeler. Rev. Mod.Phys., 1949, 21, p.144.
7. These experiments gave upper limits as bad as $R = \frac{\mu \rightarrow e\gamma}{\mu \rightarrow \text{all}} \leq 10\%$. Values of R were greatly improved in a number of experiments, the best of which, performed with a gamma hodoscope and a magnetic spectrometer, gives a limit as good as $R \leq 2 \cdot 10^{-10}$ at the 90% c.l. (Anderson, Hofstadter et al. Proc. of the Tokyo International Conference, 1978). For other similar processes the following limits are obtained $R' = \frac{\mu \rightarrow 3e}{\mu \rightarrow \text{all}} \leq 2 \cdot 10^{-9}$ (Korenchenko et al. Proc of the ν'77 Conference and $R'' = \frac{\mu^- + {}^{32}S \rightarrow e^- + {}^{32}S}{\mu^- + {}^{32}S \rightarrow \nu_\mu + \ldots} \leq 1.5 \cdot 10^{-10}$ (Baderstcher et al. Phys.Rev.Lett., 1977, 39, p.1383).
8. Wick, Wightman, Wigner. Phys.Rev., 1952, 88, p.101.
9. Bethe. Phys.Rev., 1939, 55, p.434.
10. Gamow, Schonberg. Phys.Rev., 1941, 59, p.539.
11. Pontecorvo. National Res. Council Canada, Rep. PD 205, 1946; Helv.Phys.Acta, Suppl., 1950, 3, p.97.
12. Gamow. Phys.Rev., 1948, 70, p.505.
13. Fowler. Appl.J., 1958, 127, p.551.

14. Pontecorvo. JETP, 1959, 36, p.1615.
15. Markov. Proc. of Int. Conf. on High Energy Phys., Rochester, 1960, p.578.
16. Greisen. Proc. Int. Conf. on Instrument. High Energy Phys., Interscience Publ., 1960, p.209.
17. Pontecorvo, Smorodinsky. JETP, 1961, 41, p.239.
18. Zeldovich, Smorodinsky. JETP, 1961, 41, p.907.
19. Pontecorvo. Phys.Lett., 1963, 1, p.287.
20. Reines et al. Proc. of the ν'72 Conf., vol.2, p.199.
21. Krishnasvami et al. Proc.Roy.Soc., 1971, A323, p.489; Osborne et al. Proc. of the ν'72 Conf., vol.2, p.223.
22. Fowler, Hoyle. The University of Chicago Press, Chicago-London, 1965.
23. Colgate, White. Astrophys. J., 1966, 143, p.626.
24. Zeldovich. Letters JETP, 1965, 1, p.40.
25. Domagatsky, Zetsepin. Proc. 9th Int.Conf. on Cosmic Rays, 1965, 2, p.1030.
26. Penzias, Wilson. Ap.J., 1965,142, p.419.
27. Dicke et al. Ap.J., 1965, 142, p.414.
28. Zeldovich, Novikov. Lett.JETP, 1967, 6, p.772.
29. Weinberg. Gravitation and cosmology. John Wiley Inc., New York, 1972.
30. Gershtein, Zeldovich. Letters to JETP, 1966, 4, p.174. For cosmological bounds on the mass of neutral leptons: see: Lee, Weinberg. Phys.Rev.Lett., 1977, 39, p.165; Dolgov, Visotsky, Zeldovich. Lett. JETP, 1977, 26, p.200. For cosmological bounds on the number of massless neutrino see: Schvartsman. Lett.JETP, 1969, 9, p.315; Steigman, Schram, Gunn. Phys.Lett., 1977, 66B, p.202. See also for other limits on neutrino properties from astrophysics considerations: Bernstein, Riderman, Feinberg. Phys.Rev., 1963, 132, p.1227; Berg, Marciano, Ruderman. Phys.Rev., 1978, D17, p.1395.
31. Pontecorvo. JETP, 1967, 53, p.1717; 1971, 13, p.281.
32. Gribov, Pontecorvo. Phys.Lett., 1969, 28B, p.493.
33. Bilenky, Pontecorvo. Phys.Lett., 1976, 61B, p.248; Lett.Nuovo Cimento, 1976, 17, p.569; Comments on nuclear and particle phys., 1977, 7, p.149; Phys.Rep., 1978, 41, p.226.
34. Bahcall. Proc. of the ν'72 Conference, vol.1, p.29.
35. Berezinsky, Zatsepin. Sov.Phys.Usp., 1977, v.20, p.361.
36. Gershtein et al. Proc. of the ν'77 Conf., vol.1, p.106. See also Sutherland et al. Phys.Rev., 1976, D13, p.2700; Pethick. Proc. of the ν'79 Conf., Bergen, Norway, vol.1, p.78.

37. Chudakov et al. Proc. of the ν'77 Conf., vol.1, p.155.
38. Dolgoshein et al. Proc. of the ν'77 Conf., vol.2, p.341.
39. Sulak et al. Proc. of the ν'77 Conf., vol.2, p.350.
40. Domogatsky et al. Proc. of the ν'77 Conf., vol.1, p.115.
41. Davis et al. Proc. of the ν'78 Conf., p.53. The measured rate can be compared with the theoretical rate, which is about twice larger. At this time the computed expected rate is given by Bahcall in: 40 years of stellar energy, Bethe Symposium, Stony Brook, N.Y., 1979.
42. Landé et al. Proc. of the ν'78 Conf., p.887.
43. Zatsepin. Proc. of the ν'78 Conf., p.881.
44. See for example: Learned. Proc. of the ν'78 Conf., p.895,
45. Bethe, Peierls. Nature, 1934, 133, p.532.
46. Fermi. Nuovo Cimento, 1934, vol.1, No.11.
47. Reines, Cowan. Phys.Rev., 1953, 98, p.492; 1959, 113, p.273.
48. Danby et al. Proc. High Energy Conf. at CERN 1962, p.809.
49. Vasilevsky et al. Phys.Lett., 1962, 1, p.345.
50. Kobzarev, Okun. JETP, 1961, 41, p.1205.
51. Kirkwood, Hanna, Pontecorvo. Phys.Rev., 1949, 75, p.982.
52. Davis. Phys.Rev., 1955, 97, p.766.
53. Pontecorvo. JETP, 1957, 33, p.549.
54. Pontecorvo. JETP, 1959, 37, p.1751.
55. Nguyen Van Hieu, Pontecorvo. JETP Lett., 1968, 7, p.137.
56. Pontecorvo, Ryndin. Proc. Kiev Int. High Energy Phys. Conf., 1959, p.233.
57. Bludman. Nuovo Cimento, 1958, 9, p.433.
58. Zeldovich. JETP, 1959, 36, p.964; Bouchiat, Bouchiat. Phys.Lett., 1974, 48B, p.111.
59. Barkov and Zolotarev. Proc. of the ν'78 Conf., p.423.
60. Prescott et al. Phys.Lett., 1978, 77B, p.347.
61. See for example: Conversi. Int.Conf. of the Europ.Phys. Soc., Geneva, 1979.

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