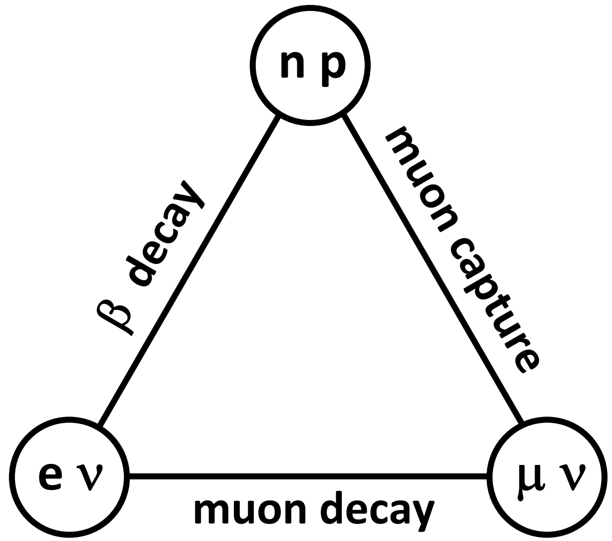
The Birth of Lepton Universality and the Second Neutrino

Luigi Di Lella
Physics Department, University of Pisa

- My first encounter with Bruno Pontecorvo's scientific work
- When and where I first met Bruno Pontecorvo in person

The Legacy of Bruno Pontecorvo: the Man and the Scientist
Rome, September 11-12, "La Sapienza" University

Graphic representation of the Universal Fermi Interaction in the 1950s: Puppi's triangle



G. Puppi, Nuovo Cimento <u>5</u> (1948) 587 (*in Italian)*

Nuclear Capture of Mesons and the Meson Decay

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

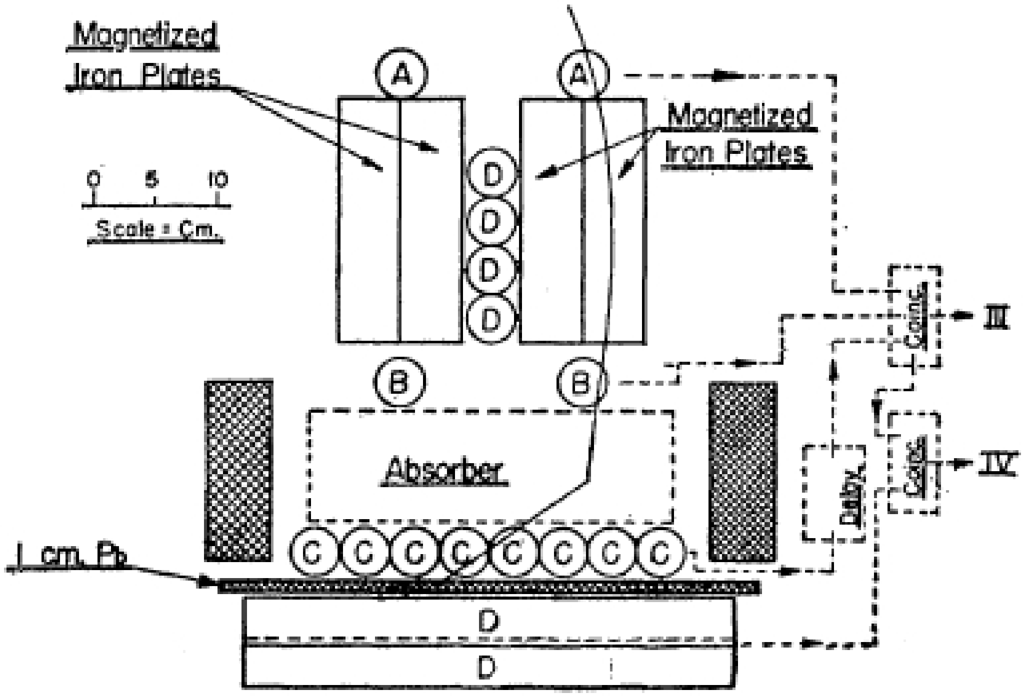
THE experiment of Conversi, Pancini, and Piccioni[1] indicates that the probability of capture of a meson by nuclei is much smaller than would be expected on the basis of the Yukawa theory.[2,3] Gamow[4] has suggested that the nuclear forces are due exclusively to the exchange of neutral mesons, the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

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

Phys. Rev 72 (1947) 246

A short reminder:

- In 1947 π mesons had not yet been discovered.
- The muon (discovered in the cosmic radiation by Anderson and Neddermeyer in 1936) had been identified as the boson postulated by Yukawa to carry the interaction between nucleons in a nucleus. It was first named “mesotron” or “meson”.
- In 1940 Tomonaga and Araki had predicted that negative mesons at rest would form “mesonic atoms” and undergo nuclear capture, while positive mesons would be repelled by nuclei and decay.
- However, an experiment performed in Rome by Conversi, Pancini and Piccioni with magnetic selection of the charge sign of cosmic rays found in 1946 that a very large fraction of negative “mesons” decayed when coming to rest in Carbon.



Layout of the experiment by Conversi, Pancini and Piccioni Phys. Rev. 71 (1947) 209

Quoting Louis Alvarez (Nobel lecture ,1968):
As a personal opinion, I would suggest that modern particle physics started in the last days of World War II, when a group of young Italians, Conversi, Pancini, and Piccioni, who were hiding from the German occupying forces, initiated a remarkable experiment.

Compare electron and muon capture rate in light nuclei under the assumption that the two processes are due to the same interaction:

$$e^- + p \rightarrow \nu + n \quad ; \quad \mu^- + p \rightarrow \nu + n$$

For light nuclei (e.g., Carbon)

$$\frac{\text{Muon capture rate}}{\text{Electron capture rate}} = \frac{|\psi_\mu(0)|^2}{|\psi_e(0)|^2} \times \left(\frac{p_\nu^\mu}{p_\nu^e}\right)^2 = \left(\frac{R_e}{R_\mu}\right)^3 \times \left(\frac{p_\nu^\mu}{p_\nu^e}\right)^2 = \left(\frac{m_\mu}{m_e}\right)^3 \times \left(\frac{p_\nu^\mu}{p_\nu^e}\right)^2 \approx 208^3 \times 100^2 \approx 10^{11}$$

A brilliant intuition despite the very large difference of the two capture rates (two sides of Puppi's triangle)

In the same paper one can also read:

.... We shall consider then the hypothesis that the meson has spin $\frac{1}{2}\hbar$ and that its instability is not a β-process, in the sense that it does not involve the emission of one neutrino. The meson decay must then be described in a different way: it might consist of the emission of an electron and a photon or of an electron and 2 neutrinos[5] or some other process.

Yukawa had suggested that the meson decays to electron + neutrino

**This paper suggests that the cosmic ray "meson" behaves like a heavy electron.
In my opinion, this paper represents the birth of muon – electron universality.
An interesting question is, why was this paper ignored?
(for example, it is not cited in Puppi's paper)**

The second neutrino

"Forbidden processes"

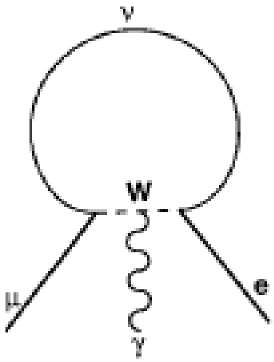
$\mu^+ \rightarrow e^+ + \gamma$: **measurement of** $R_{e\gamma} = \dfrac{\Gamma(\mu^+ \rightarrow e^+\gamma)}{\Gamma(\mu^+ \rightarrow e^+\nu\overline{\nu})}$

- $R_{e\gamma} < 0.01$
  E. Hincks and B. Pontecorvo, 1948 (cosmic rays)
- $R_{e\gamma} < 2 \times 10^{-5}$
  S. Lokanathan and J. Steinberger, 1955 (at the Nevis synchrocyclotron)
- $R_{e\gamma} = (1.2 \pm 1.2) \times 10^{-6}$
  J. Ashkin et al., 1959 (at the CERN synchrocyclotron)

Theoretical prediction

G. Feinberg, 1958

$R_{e\gamma} \approx 10^{-4}$



An important theoretical remark (Cabibbo & Gatto, Feinberg & Weinberg 1960) **:**
the $\mu \rightarrow e + \gamma$ transition amplitude may be very small (or even zero) for real photons, while being large for virtual photons

Search for neutrinoless μ^- capture in Copper : measure

$$R = \frac{\text{Rate of } \mu^- + Cu \rightarrow e^- + Cu}{\text{Rate of } \mu^- + Cu \rightarrow \nu + Ni^*}$$

- ***R*** **< 5** x **10^{-4}**
  J. Steinberger and H.B. Wolfe, 1955 (at the NEVIS synchrocyclotron)
- ***R*** **< 5.9** x **10^{-6}**
  M. Conversi et al., 1960 (at the CERN synchrocyclotron)
- ***R*** **= (4 ± 3)** x **10^{-6}** **(3 events, estimated background 0.23 events)**
  Sard, Crowe and Kruger, 1960 (at the Berkeley synchrocyclotron)
- ***R*** **< 2.4** x **10^{-7}**
  M. Conversi et al., 1961 (at the CERN synchrocyclotron)

SOVIET PHYSICS JETP VOLUME 37(10), NUMBER 6 JUNE, 1960

ELECTRON AND MUON NEUTRINOS

B. PONTECORVO

Joint Institute for Nuclear Research

Submitted to JETP editor July 9, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **37**, 1751-1757 (December, 1959)

Some processes due to free neutrinos, not heretofore considered, are discussed. Particular attention is paid to those processes which, in principle, could help decide whether two neutral lepton pairs [electron pair (ν_e and $\bar{\nu}_e$) and muon pair (ν_μ and $\bar{\nu}_\mu$)] exist.

To answer the fundamental question about the identity of ν_μ and ν_e a method is proposed which in essence is analogous to the method used to distinguish neutrinos from antineutrinos or K^0 mesons from $\bar{K}^0$ mesons. In principle the problem is solved when an experiment is carried out showing whether a beam of $\bar{\nu}_\mu$ is capable of initiating transitions which can without any doubt be initiated by $\bar{\nu}_e$ (for example the reaction $\bar{\nu}_\mu + p \rightarrow e^+ + n$).

The suggested experiment, although difficult, should be feasible with accelerators capable of producing more intense beams then those produced by present-day accelerators.

In our case we are concerned not with the already settled problem about the distinction between neutrino and antineutrino but rather with the distinction between ν_e and ν_μ (or $\bar{\nu}_e$ and $\bar{\nu}_\mu$). If ν_e and ν_μ are different then it is already known which reactions should produce ν_e and $\bar{\nu}_e$ and should not produce ν_μ and $\bar{\nu}_\mu$ (and vice versa).

To settle the question it is necessary to ascertain experimentally whether a beam of $\bar{\nu}_\mu$ is capable of inducing transitions which can definitely be induced by $\bar{\nu}_e$. From the experimental point of view a beam of muon neutrinos is more attractive than a beam of electron neutrinos for the following reasons. The usual intense sources of electron neutrinos are radioactive isotopes. Their very nature makes them incapable of emitting high energy neutrinos. A good source of muon neutrinos is the π-μ decay in which the neutrinos are produced with high energies. It would be of interest to use a high energy antineutrino, say $\gg$ 100 Mev, since the cross section for neutrino induced processes grows rapidly with energy. However at very high energies the intensity of generation of muon neutrinos is reduced due to the relativistic increase in the lifetime of the π mesons and therefore we shall discuss an experiment for a neutrino with energy < 100 Mev.

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n, \qquad \text{(a)}$$

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

The reaction (b), if ν_e and ν_μ are identical, was successfully observed by Reines and Cowan,[4] and if $\nu_e \neq \nu_\mu$, the reaction is unobservable. The reaction (a) is a threshold reaction and therefore can never be observed for ν_μ energies < 100 MeV The problem is to determine the cross section for reaction (b). When the neutrons from reaction (b) are in the energy region where their detection is possible with good efficiency inside a large scintillation counter containing cadmium, the method of Reines and Cowan is fully applicable. When the event caused by reaction (b) takes place two pulses will appear in the scintillation counter, one corresponding to the release of the positron energy (the neutron receives a small share of the energy) and the other, delayed with respect to the first one, corresponding to the release of the photon energy from the neutron capture in cadmium. To detect the reaction (b) a Reines and Cowan type scintillation counter may be placed in a beam of muon antineutrinos incapable of inducing reaction (a) (for energy reasons) and containing a negligibly small admixture of electron antineutrinos which could cause the "trivial" reaction $\bar{\nu}_e + p \rightarrow e^+ + n$.

Pontecorvo's proposal: a "beam dump" experiment using a medium-energy proton machine (in the article he writes 700 MeV kinetic energy).

Most negative pions coming to rest in the dump are absorbed.

In the decay chain $\pi^+ \rightarrow \mu^+ + \nu$; $\mu^+ \rightarrow \bar{\nu} + e^+ + \nu$ the only source of $\bar{\nu}$ is μ^+ decay. They are under threshold for muon production, but they can produce e^+ if $\bar{\nu}_\mu \equiv \bar{\nu}_e$. The reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ is detected as in the Reines – Cowan experiment (prompt signal from e^+ and annihilation to two γ – rays, delayed signal from neutron capture in Cadmium)

Pontecorvo's conclusion: existing proton accelerators have not enough beam intensity to perform the experiment:

To sum up one could say that an experiment to establish the identity of ν_e and ν_μ, although very difficult, should be seriously considered in the planning of new accelerators. In particular the problem of shielding of the $\bar{\nu}_\mu$ detector from radiation should be looked to in the very first stages of design.

Indeed, experiments very similar to the one proposed by Bruno have been performed in the 1990's at Los Alamos (LSND) and at ISIS (KARMEN) using 800 MeV high-intensity proton accelerators with the purpose of measuring $\bar{\nu}_\mu$ - $\bar{\nu}_e$ oscillations.

For historical interest, compare Pontecorvo's paper with the paper by Mel Schwartz, Phys. Rev Letters 4 (1960) 306

FEASIBILITY OF USING HIGH-ENERGY NEUTRINOS TO STUDY THE WEAK INTERACTIONS

M. Schwartz*
Columbia University, New York, New York
(Received February 23, 1960)

For many years, the question to how to investigate the behavior of the weak interactions at high energies has been one of considerable interest. It is the purpose of this note to show that experiments pointed in this direction, though not quite feasible with presently existing equipment, are within the capabilities of present technology and should be possible within the next decade.

We propose the use of high-energy neutrinos as a probe to investigate the weak interactions.

A natural source of high-energy neutrinos are high-energy pions.

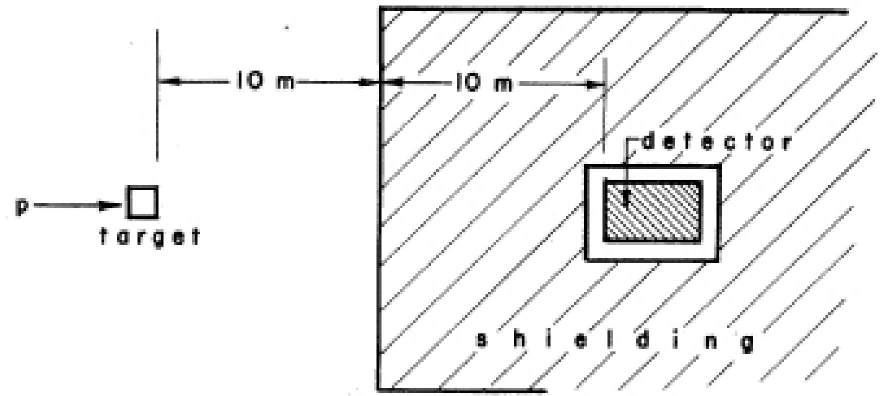


FIG. 1. Proposed experimental arrangement.

The main motivation is the study of neutrino interactions at high energies. The two – neutrino problem (is $\nu_\mu \neq \nu_e$?) is not mentioned in this paper

Mel Schwartz' conclusions:

Thus, a high-intensity 10-Bev proton machine with a beam intensity ~10^{15} protons/sec may give a counting rate of more than 10^3 per hour, using the experimental setup described above. If that proves to be the case, it is perhaps desirable to have magnetic lenses to analyze and focus the pions so as to obtain more monoenergetic neutrino beams.

I would like to express my gratitude to Dr. T. D. Lee and Dr. C. N. Yang for many stimulating discussions which led to the above proposal.

Note added in proof. The author's attention has been called to a somewhat related paper which has just appeared: B. Pontecorvo, J. Exptl. Theoret. Phys. (U.S.S.R.) 37, 1751 (1959).

Mel Schwartz' paper is followed by a paper which does mention the two – neutrino problem: T.D. Lee and C.N. Yang, Phys. Rev. Letters 4 (1960) 307

THEORETICAL DISCUSSIONS ON POSSIBLE HIGH-ENERGY NEUTRINO EXPERIMENTS*

T. D. Lee
Columbia University, New York, New York

and

C. N. Yang
Institute for Advanced Study, Princeton, New Jersey

(Received February 23, 1960)

In the preceding Letter,[1] Schwartz points out that the neutrinos from the decay of high-energy mesons can be used to study weak interactions. We have investigated the theoretical implication of such possible experiments. Efforts are made to separate and dissociate the inferences that can be drawn from different assumptions concerning the weak interactions. In this Letter we report briefly on this work.

1. The identity of the neutrinos. In the processes

$$\pi^+ \to \mu^+ + \nu_1, \qquad (\pi \text{ decay}) \qquad (1)$$

$$\mu^- + p \to n + \nu_2, \qquad (\mu \text{ capture}) \qquad (2)$$

$$Z \to (Z-1) + e^+ + \nu_3, \qquad (\beta^+ \text{ decay}) \qquad (3)$$

it is easy to see that ν_1 and ν_2 are the same particle. Experimentally it is known that ν_1 and ν_3 both have helicity -1. It is simplest to assume that ν_1 and ν_3 are also the same particle. However, a test of this assumption is clearly desirable. To obtain such a test it is necessary to do some kind of capture experiment on the neutrinos or antineutrinos. For example, if ν_1 and ν_3 are different particles, then the reaction

$$n + \nu_1 \to p + e^- \qquad (4)$$

does not occur.

Объединенный
институт
ядерных
исследований
дубна

E1,2-82-414

B.Pontecorvo

THE INFANCY AND YOUTH OF NEUTRINO PHYSICS: SOME RECOLLECTIONS

Submitted to the International Colloquium
on Particle Physics (Paris, July 1982)

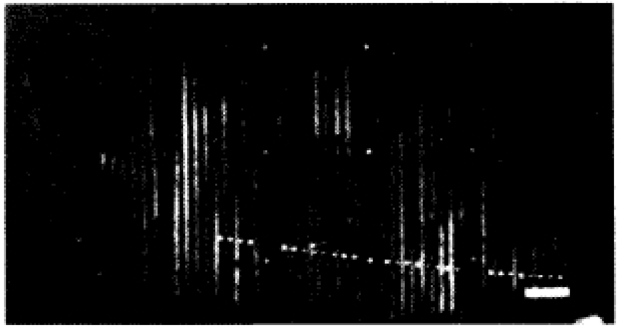
1982

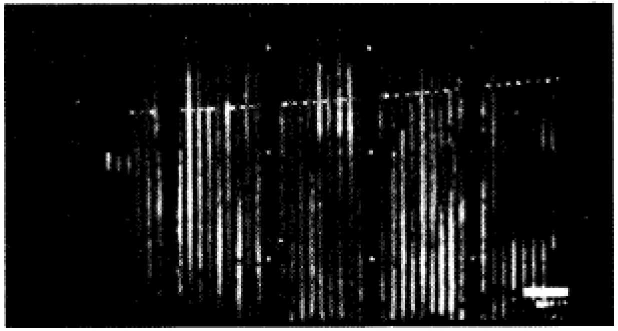
I have to come back a long way (1947-1950). Several groups, among which J.Steinberger, E.Hincks and I, and others were investigating the (cosmic) muon decay. The result of the investigations was that the decaying muon emits 3 particles: one electron (this we found by measuring the electron bremstrahlung) 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.

§11. High energy neutrino physics.-My story here is again very personal. Of course the story would sound quite different if it were told by either Markov or Schwartz. I am going 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. By the way, this accelerator eventually was not built. Anyway at the beginning of 1959 I started to think about the experimental research program for such an accelerator. First, it occurred to me that neutrino investigations at accelerator facilities are perfectly feasible and 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 for an accelerator which was not built.

In my opinion, the invention of the spark chamber (Fukui and Miyamoto, 1959) made the first high-energy neutrino experiment possible

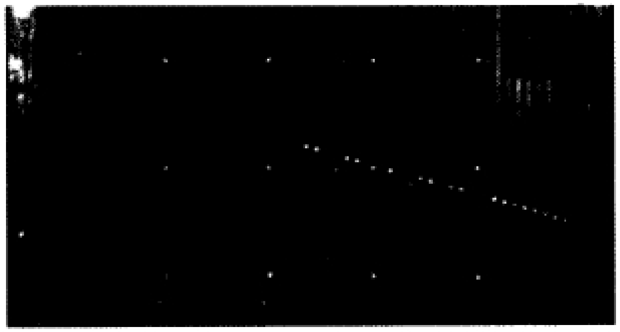
G. Danby, J.M. Gaillard, K. Goulianos, L.M. Lederman, M. Mistry, M. Schwartz, and J. Steinberger, Observation of High-Energy Neutrino Reactions and the Existence of Two Kinds of Neutrinos, Phys. Rev. Letters **9** (1962) 36





A 10 – ton neutrino detector at the AGS (BNL)

- **10 spark chamber modules**
- **1 module: 9 Aluminium plates, each 112 x 112 x 2.5 cm**



Very clear muon identification and muon – electron , muon – pion separation