Pontecorvo100 – Symposium in honour of Bruno Pontecorvo for the centennial of the birth

Pisa 18-20 September 2013

"On the history of the PMNS matrix"

…with today's perspective

IFIC INSTITUT DE FÍSICA CORPUSCULAR

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PERSONAL REMINISCENCES

- I met personally Bruno in the summer 1990, when he visited CERN at the time of the collapse of the Soviet Union. He was deeply concerned and wishful on the future of Russia. I remember him following the news by radio in the CERN office.
- Beyond political events, I was delighted in convincing him to participate in TAUP'91 meeting in Toledo.

TAUP 91

- According to notes by F. Buccella in Pontecorvo's book, when Bruno joined this meeting in the Lecture Hall, J.B. was lecturing on "Neutrino Properties" and interrupted his presentation with the greeting *"Bruno, Welcome to Spain".*
 After a moment of general complacency, the session continued.

PERSONAL REMINISCENCES

➢ The participation of Pontecorvo in Spanish events of physics had a new glorious moment

with the “Neutrino’92” Conference in Granada and the Universal Exhibition of Sevilla.

PERSONAL REMINISCENCES

- Among other exhibitions, the Canada Pavilion was special for neutrino physicists with the presentation of the SNO experiment for solar neutrino detection. The statement was: "John Bahcall is probably right. But his solar model is NOT needed for the interpretation of the solar neutrino problem"

- CERN as Meeting Point of physicists was also important in preparing a long-term visit of Samoil Bilenky, from 1991 to 1994, to Valencia. This was a period of fruitful scientific collaboration.

THE COMPONENTS

- The understanding of the beautiful properties associated to Neutrino Mixing and Oscillations has several "components" to be discussed in their historical steps:
- The Family Problem
  - μ-e Universality
  - Different $\upsilon_e - \upsilon_\mu$ Flavours
- Neutrino Mass
  - Mismatch between Weak Interaction-Mass eigenstates
  - Global L-charge ?
- Mixing & Oscillations
  - Earliest ideas
  - MNS mixing in the Nagoya model of baryons
  - Oscillation Phenomenology

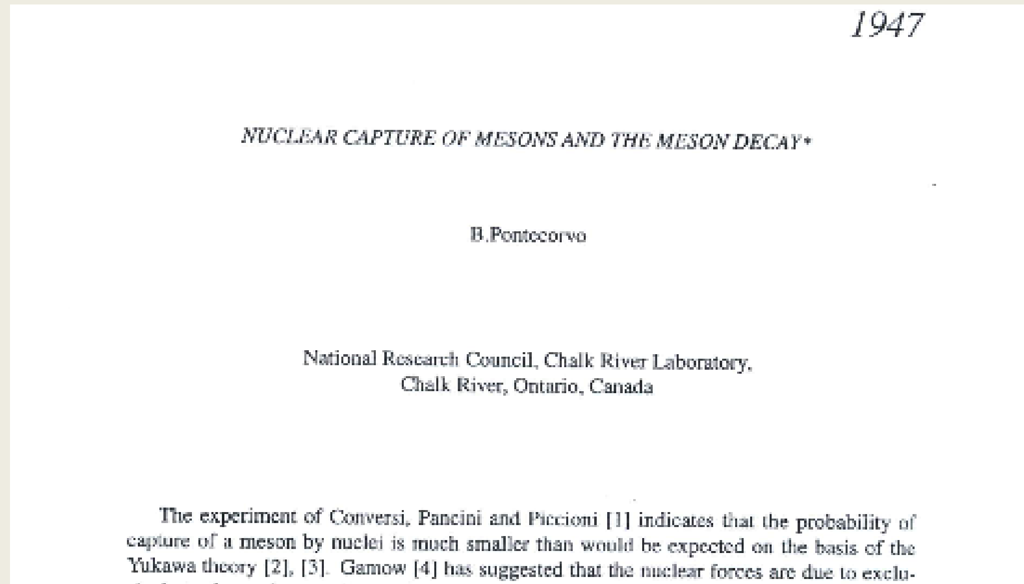
THE FAMILY PROBLEM

- μ-e Universality

➢ A decade before the (V-A) theory of (charged current) weak interactions (WI),

B. Pontecorvo, PR (1947)

discussed the "universality" of WI for processes of nuclear β-decay together with those with muon and neutrino!



1947

NUCLEAR CAPTURE OF MESONS AND THE MESON DECAY*

B.Pontecorvo

National Research Council, Chalk River Laboratory,
Chalk River, Ontario, Canada

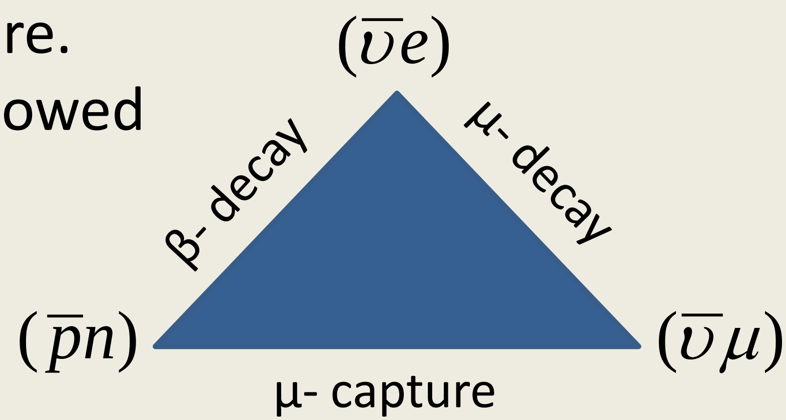
The experiment of Conversi, Pancini and Piccioni [1] indicates that the probability of capture of a meson by nuclei is much smaller than would be expected on the basis of the Yukawa theory [2], [3]. Gamow [4] has suggested that the nuclear forces are due to exclu-

He introduced

μ – capture $\mu^- + (A,Z) \rightarrow \upsilon + (A, Z-1)$

and compared with probability for e-capture.

➢ The idea of μ-e universality was also followed by G. Puppi, NC(1948) with the famous "Puppi triangle"



<u>Question: The same υ in the two vertices?</u>

LEPTON FLAVOUR NUMBER

- The idea of different neutrinos υ_e, υ_μ appeared published in the paper

  B. Pontecorvo, J Phys. (1959)

  and, more important, in the proposal made by Pontecorvo of the Brookhaven experiment that discovered υ_μ!

  B. Pontecorvo, Sov. Phys. JETP (1960)

1959

ELECTRON AND MUON NEUTRINOS*

B.Pontecorvo

Joint Institute for Nuclear Research, Dubna

The cross section for β-particle production in the collision of free neutrinos with nuclei was first evaluated in 1934 by Bethe and Peierls [1]. As is well known, the cross section for 1 MeV neutrinos was expected to be 10^{-44} cm^2. Because of this for a long time the effects induced by free neutrinos were considered unobservable. Later on, it

- The Brookhaven υ experiment was the first with high energy υ's from π decay. It was a great event in physics and TWO LEPTON FAMILIES COMPLETED

  $$(\upsilon_e, e) \& (\upsilon_\mu, \mu)$$

  G. Danby et al., PRL (1962)

1960

EXPERIMENTS WITH NEUTRINOS EMITTED BY MESONS

B.Pontecorvo

Joint Institute for Nuclear Research, Dubna

Recently there were widely discussed the possibilities of using beams of high energy neutrinos emitted by mesons to get information on weak interactions [1,2,3,4,5].

In the papers [3,4] it has been shown that the form-factors related to the presence of strong interacting particles suppress the increase with energy of the cross sections

- An earlier indication $\upsilon_e \neq \upsilon_\mu$:

  The search for the decay $\mu \rightarrow e\gamma$

- G. Feinberg, PR (1958) estimated the BR in the V-A theory with the W-boson if

  $$\upsilon_e = \upsilon_\mu \rightarrow R_{th} \sim 10^{-4}, \quad R_{exp} < 10^{-8}$$

UP'S & DOWN'S NEUTRINO MASS

- PV in processes involving υ's → <u>Advent of Two-component υ theory</u>

If υ's are exactly massless

$$i\gamma^{\mu}\partial_{\mu}v_L(x) - m_{v}v_R(x) = 0$$

- Goldhaber experiment,

M. Goldhaber et al., PR(1958)

proved that υ -helicity is -1 → υ_L !

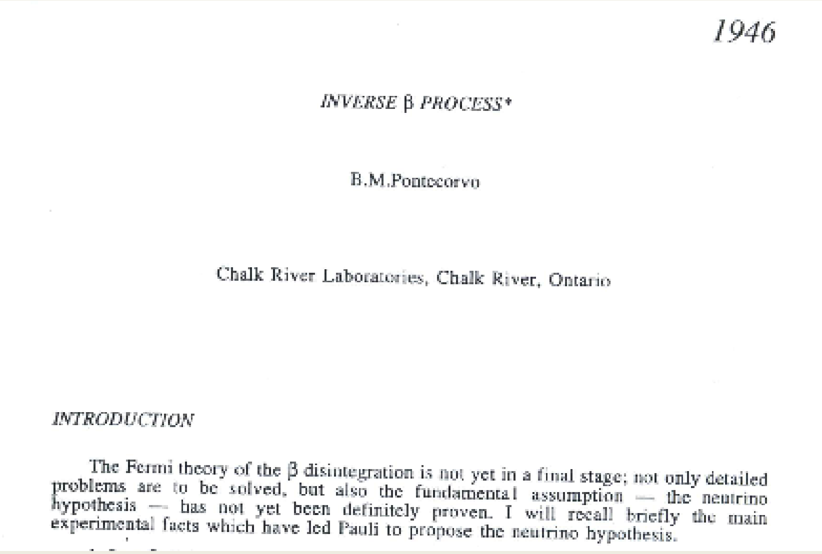
- But … Universal V-A theory of WI tells that L-handed Chiral Fields enter for ALL Fermions → <u>No rationale why υ's are special and massless.</u>

- Still, contrary to other fermions, υ's have no electric charge. Do they have a Lepton Charge? OPEN Question in 2013! :

GLOBAL LEPTON NUMBER

- Pontecorvo proposal (1946)! :
  - $\overline{\upsilon}$'s produced in β^- decay in Reactors,

Can them produce e's ?
  - Davis (1959), BAPS (1959)



1946

*INVERSE β PROCESS**

B.M.Pontecorvo

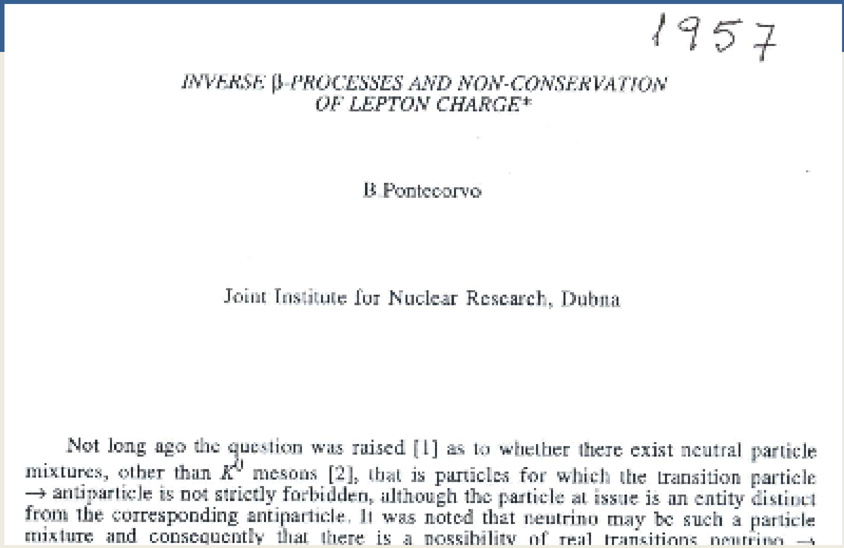
Chalk River Laboratories, Chalk River, Ontario

INTRODUCTION

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

$$\overline{v} + {}^{37}Cl \not\rightarrow e^- + {}^{37}Ar \longrightarrow \left.\begin{array}{l} L_{e^-} = L_{v} = +1 \\ L_{e^+} = L_{\overline{v}} = -1 \end{array}\right\}$$

MIXING AND OSCILLATIONS


1957

*INVERSE β-PROCESSES AND NON-CONSERVATION OF LEPTON CHARGE**

B Pontecorvo

Joint Institute for Nuclear Research, Dubna

Not long ago the question was raised [1] as to whether there exist neutral particle mixtures, other than K^0 mesons [2], that is particles for which the transition particle → antiparticle is not strictly forbidden, although the particle at issue is an entity distinct from the corresponding antiparticle. It was noted that neutrino may be such a particle mixture and consequently that there is a possibility of real transitions neutrino →

- Words of Pontecorvo in 1957 (!):

" If the theory of two component neutrino was not valid, and if the conservation law for <<neutrino charge>> took not place, neutrino ⟷antineutrino transitions would be possible".

- Early ideas in *B. Pontecorvo, J. Expt. Theor. Phys. (1957)* are discussed in analogy with Gell-Mann & Pais theory of $K^0 \Leftrightarrow \overline{K}^0$ mixing and oscillations.
- Instead of only υ_L *and* $(\bar{\upsilon})_R$, Bruno assumed <u>additional</u> $(\bar{\upsilon})_L$ and υ_R states ["sterile" is his name]. For the Davis experiment,

Active-Sterile Mixing $\quad (\bar{\upsilon})_R \Leftrightarrow \upsilon_R$

with two Majorana massive states $\quad \upsilon_1 = \frac{1}{\sqrt{2}}\left[(\bar{\upsilon})_R + \upsilon_R\right], \qquad \upsilon_2 = \frac{1}{\sqrt{2}}\left[(\bar{\upsilon})_R - \upsilon_R\right]$

- His OSCILLATION result

Appearance $\quad P\left[(\bar{\upsilon})_R \xrightarrow{L} \upsilon_R\right] = \frac{1}{2}\left(1-\cos\frac{\Delta m^2 L}{2E}\right)$ $\quad$ Davis

Survival $\quad P\left[(\bar{\upsilon})_R \xrightarrow{L} (\bar{\upsilon})_R\right]$ $\quad$ Reines - Cowan

- Pontecorvo in 1958: *"It would be extremely interesting to perform the Reines-Cowan experiment <u>at different distances from reactor</u>". KamLAND (2003) observed the effect.*

NEUTRINO MIXING FOR BARYON MODEL

- The "Unified" Model? → Nagoya model of Baryons as bound states of neutrinos and " a new sort of matter" vector boson. The "true neutrinos" in these baryons would be

$$\left.\begin{aligned} \upsilon_1 &= \cos\delta\upsilon_e - \sin\delta\upsilon_\mu \\ \upsilon_2 &= \sin\delta\upsilon_e + \cos\delta\upsilon_\mu \end{aligned}\right\} \Leftrightarrow$$

δ would be the Cabibbo angle, to explain small leptonic decay rate of hyperons.

Remarks on the Unified Model of Elementary Particles

1962

Ziro Maki, Masami Nakagawa and Shoichi Sakata
+ Author Affiliations

Received June 25, 1962

Abstract

A particle mixture theory of neutrino is proposed assuming the existence of two kinds of neutrinos. Based on the neutrino-mixture theory, a possible unified model of elementary particles is constructed by generalizing the Sakata-Nagoya model. Our scheme gives a natural explanation of smallness of leptonic decay rate of hyperons as well as the subtle difference of G_V's between μ-*e* and β-decay.

- The MNS neutrino mixing was not associated to the quantum phenomenon of υ oscillations: the interference of different mass eigenstates.
- υ_2 , on the contrary, would have additional interaction with a field of heavy particles X. In MNS words,

  " Weak υ's are not stable due to the occurrence of virtual transition $\upsilon_e \Leftrightarrow \upsilon_\mu$ caused by this additional interaction with υ_2 "

OSCILLATION PHENOMENOLOGY

➢ In the 1960's, after the discovery of υ_μ , Pontecorvo discussed the phenomenology of υ oscillations in modern views:

Flavour $\upsilon_e \Leftrightarrow \upsilon_\mu; \quad \upsilon_e \Leftrightarrow \left(\bar{\upsilon}_e\right)_L; \quad \upsilon_\mu \Leftrightarrow \left(\bar{\upsilon}_\mu\right)_L$

and applied, among other subjects,
<u>to Solar υ Oscillations</u>

- In the paper with Gribov, one reads (in 1969!): " If Global Lepton Number is violated, neutrinos will have a mass of Majorana type"
- In the paper with Bilenky, they discuss Oscillation for Reactor and Accelerator Experiments

1967

*NEUTRINO EXPERIMENTS AND THE QUESTION OF LEPTONIC-CHARGE CONSERVATION**

B.Pontecorvo

Joint Institute for Nuclear Research, Dubna

When Gilberto Bernardini came to Dubna for the 1964 International Conference on High-Energy Physics, he was very interested in the problem of lepton conservation, on which he had informal discussions with several physicists. The present speculations are a continuation of our conversations in Dubna, and are intended to draw the attention of physicists to some theoretical and experimental problems which are to be solved.

1969

*NEUTRINO ASTRONOMY AND LEPTON CHARGE**

V.Gribov**, B.Pontecorvo***

**Leningrad Physical-Technical Institute, Leningrad, USSR

***Joint Institute for Nuclear Research, Dubna

It is shown that lepton nonconservation might lead to a decrease in the number of detectable solar neutrons at the earth surface, because of $\nu_e \rightleftarrows \nu_\mu$ oscillations, similar to $K^0 \rightleftarrows \bar{K}^0$ oscillations. Equations are presented describing such oscillations for the case when there exist only four neutrino states.

1976

*OSCILLATIONS IN NEUTRINO BEAMS: STATUS AND POSSIBILITIES OF OBSERVATION**

S.M.Bilenky, B.Pontecorvo

Joint Institute for Nuclear Research, Dubna

This review paper deals with the problem of possible oscillations in vacuum between different neutrino states. The ultimate sensitivity of oscillation experiments at various neutrino facilities (Sun, reactors, accelerators) is given in terms of a parameter, which is a function of the neutrino masses. Possible experiments are of the relative type, when one would look for a cosinusoidal term in the intensity of detected neutrinos, and of the absolute type, when the cosinusoidal term is vanishing as a result of averaging, and one would compare the absolute intensity of neutrinos of a given type with that expected in absence of oscillations. Various oscillation schemas are discussed, in which the two neutrinos with definite masses are described either by Majorana or Dirac fields. Schemes with N types of neutrinos (N > 2) are presented.

CONCLUSION

- The Discovery of ν Oscillations in 1998, implying ν Mass (differences) and ν Mixing, was a great event in Science.
- With today's perspective, we condense the information in the Unitarity Mixing Matrix for (active) neutrinos:

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where the last matrix is only seen iff neutrinos are Majorana particles.

- Historically, it is spectacular that the CONCEPTS were discussed, and understood, in a period when the prevailing view was of massless neutrinos:
  - Universality & different ν Families → Pontecorvo, Brookhaven Experiment
  - Interplay of Mass & Mixing for ν Oscillations → Pontecorvo
  - ν Flavour Mixing for Baryon Structure → MNS
  - ν Oscillation Phenomenology, including Flavour & Majorana cases → Pontecorvo
- My Conclusion: It is FAIR to call the U matrix

The PMNS Matrix