Bruno Pontecorvo and neutrino physics

Ubaldo Dore
Dipartimento di Fisica, Università di Roma “La Sapienza”,
and I.N.F.N., Sezione di Roma, P. A. Moro 2, Roma, Italy

Lucia Zanello
Dipartimento di Fisica, Università di Roma “La Sapienza”,
and I.N.F.N., Sezione di Roma, P. A. Moro 2, Roma, Italy
Abstract

In this paper the contribution of Bruno Pontecorvo in the field of neutrino physics will be illustrated. Special emphasis will be given to the physics of oscillations that he was the first to propose.
Contents

0.1 Introduction . . . . . . . . . . . . . . . . 3
0.2 History of neutrino . . . . . . . . . . . . 4
  0.2.1 The birth of neutrino . . . . . . . 4
  0.2.2 The detection of neutrino . . . . 5
  0.2.3 Present knowledge of neutrino physics 6
0.3 Biography . . . . . . . . . . . . . . . . 7
0.4 Scientific activity . . . . . . . . . . . . . 11
  0.4.1 Activities in Canada . . . . . . . 12
  0.4.2 Activities in Dubna . . . . . . . 18
0.5 Oscillations . . . . . . . . . . . . . . . . 20
  0.5.1 Basics of neutrino oscillation theory 21
  0.5.2 Experimental results . Solar neutrinos 23
  0.5.3 Experimental results . Atmospheric neutrinos 29
  0.5.4 The contribution of Bruno Pontecorvo 31
  0.5.5 Present knowledge of the Pontecorvo-
        Maki-Nakagawa-Sakata matrix . . 33
0.6 References 

36
0.1 Introduction

This paper is dedicated to illustrate the Bruno Pontecorvo contribution to neutrino Physics.

BP contribution to neutrino physics make him one the major contributors to the development of particle physics in the XX century. His ideas and proposals were then the subject of many successful experiments that gave to their authors Nobel Prize award. We will describe his ideas in this paper. Many ideas about neutrino physics were put forward by BP much in advance of the times. The most important were:

- As soon as nuclear reactors were built he realized the fact that the produced intense flux of neutrinos would have made the detection of these particles possible at a time in which many physicists thought that this observation was impossible.

- He suggested the use of the neutrino chlorine reaction that was then used in the Homestake experiment that started the experimental oscillation physics.

- The results of the Conversi-Pancini-Piccioni experiment brought him to a first introduction of the concept of Universality in weak interactions.

- Neutrino experiments at accelerators and the exis-
tence of two types of neutrino was anticipated by BP.

• The hypothesis of neutrino mixing and so of oscillations was put forward by BP. The existence of oscillations and so the fact that neutrinos have mass has been one of the most important results of particle physics in the last years.

The paper is organized in the following way

• Brief introduction to neutrino physics
• Biography of Bruno Pontecorvo
• The scientific production
• The big intuition ”OSCILLATIONS”.

0.2 History of neutrino

0.2.1 The birth of neutrino

In 1930 Pauli \cite{1} suggested, to save energy conservation in beta decay, that a neutral light particle was emitted in the process, he named it \textit{neutron} in June 1931.

In 1932 the neutron was discovered by Chadwick \cite{2} so the new Pauli particle was called \textit{neutrino} by E. Fermi.
0.2.2 The detection of neutrino

The smallness of cross section made the neutrinos still a hypothesis; many physicists thought that neutrino detection was almost impossible.

Pontecorvo showed [23] (see paragraph 0.4.1) that in fact the detection could be possible.

The detection of free neutrinos was accomplished by Cowan and Reines [26] who observed the reaction

$$\bar{\nu}_e + p \rightarrow n + e^+$$

This experiment was the first to detect free neutrinos and
Reines was awarded the Nobel prize in 1995.

0.2.3 Present knowledge of neutrino physics

For a complete review of current status of knowledge on neutrino physics see [3]

We summarize briefly our present knowledge of neutrino properties:

- Neutrinos are chargeless fermions interacting only through weak interactions.
- Neutrinos interact through the exchange of W (charged currents) or Z0 (neutral currents).
- the V-A theory requires, in the limit of massless neutrinos, that only left handed neutrinos be active. The opposite is true for antineutrinos.
- In the Minimum Standard Model (MSM) there are 3 type of massless neutrinos (we shall see that the massless condition must be relaxed) and a corresponding number of antineutrinos.
- Weak interactions have the same strength for the three species, (Universality).
- Neutrinos are coupled to the corresponding charged leptons so we have 3 leptonic doublets
\[
\begin{pmatrix}
  e^- \\
  \nu_e
\end{pmatrix},
\begin{pmatrix}
  \mu^- \\
  \nu_\mu
\end{pmatrix},
\begin{pmatrix}
  \tau^- \\
  \nu_\tau
\end{pmatrix}.
\]

- Leptons in each doublet carry an additive leptonic number \( L_e, L_\mu, L_\tau \), which has opposite sign for antiparticles.
- Leptonic numbers are separately conserved.

There are still questions that must be answered. Are neutrinos Dirac or Majorana particles?
Neutrinos have a mass but the absolute scale of this mass is still unknown.

### 0.3 Biography

Bruno Pontecorvo was born in Pisa in 1913 from a known Jewish family. He had three brothers and two sisters, one brother was Guido (1907-1999) professor of genetics, the other was Gillo (1919-2008) the well-known film director. In 1929 he left Pisa and enrolled in the third year of the degree in Physics at the University of Rome. After his graduation he became the youngest member of the Fermi Group. In 1934 he collaborated to the famous experiment on slow neutrons [11], [12].

In 1936 he moved to Paris in the Joliot Curie laboratory. He was of a Jewish family, so after the German invasion
he had to flee to Spain and then to the United States with his family: his wife Marianne Nordblon and his first son Gil. He found a job in an oil search company. In 1943 he was called to participate to the construction of a nuclear reactor in Canada. He stayed there until 1948. In that period his sons Tito and Bruno were born. In 1948 he became a British citizen and moved to England called by J. Cockroft. In 1950 he traveled to Italy, officially on holiday. He went with his family to Stockolm and then to the Soviet Union in the Dubna laboratories. In Soviet union he was called Bruno Maximovic. From Dubna he made several trips to Italy starting in 1978.

Figure 2: Bruno Pontecorvo, Emilio Segre and Edoardo Amaldi in Rome 1978

The last ten years of BP life were a courageous struggle
against Parkinson disease. He never stopped to work on physics and oscillations

Figure 3: Dubna 1988 Neutrino oscillations

He remained in the Soviet Union until his death in 1993. Now his tombstone is in the Cimitero Acattolico in Rome. the tomstone is shown in figure 4

For the reasons that made him decide to go to the Soviet Union one can quote the words of V.P. Dzhelepov [22], a distinguished russian physicist:

Bruno was an Italian communist, at the time of arrival in the Soviet Union he was a communist-idealist sincerely believing in the strength and rightness of the type of development chosen by Russia.
It must be noted that there was a malevolent interpretation of his arrival in USSR: he was a soviet spy and he fled before being unmasked.

The Impact of BP on neutrino physics is well recognized in the Scientific world.

We will give three examples:

Valentine Telegdi quoted by L. Okun [?]

Almost all important idea in neutrino physics are due to Pontecorvo

Jack Steinberger [?]
Few of us in particle physics can boast of a single original and important idea. Bruno wealth of seminal suggestions establish him as a truly unique contributor to the advance of particle physics in the past half century.

Nicola Cabibbo [2]

Con Pontecorvo scompare uno dei grandi scienziati del XX secolo uno dei pionieri della fisica delle alte energie.

0.4 Scientific activity

BP started his scientific activity in Rome in the group of E. Fermi, participating to the famous experiments on the slowing down of neutrons in hydrogenous materials [11],[12].

From 1936 to 1938 he worked in Paris with F. Joliot Curie on nuclear isomerism [13].

From 1938 to 1940 he worked in the 'Well survey inc', Tulsa USA where he developed a system [14] for finding oil or water underground. The system used a neutron source and was the first application of the Rome results on the slowing down of neutrons. In the following, activities in Canada and Dubna will be presented.
0.4.1 Activities in Canada

BP lived in Canada from 1943 to 1950. At the beginning he stayed in Montreal where he worked on the NRX project, a heavy water, natural uranium reactor. He worked on the design of the reactor that started in 1947 yielding a flux of $6 \times 10^{15} \bar{\nu}_e / \text{cm}^2 \text{ sec}$

The reactor was then built near the Chalk river, and he lived in the nearby Deep River town. We want to recall his contributions on the following arguments

- muon decay
- universality
- neutrino detectors
- proportionals counters

muon decay

In 1950 he published, together with E.P.Hincks [15], the result of an experiment on the decay of the penetrating cosmic ray particle, the muon, that was known to have a 2.2 $\mu$s lifetime, while decay products were not known. The only thing known was that one charged particle was emitted but there was no information on its nature and on the nature of the emitted neutral particle(s). In the experiment, muons were stopped in an absorber and were
detected by an arrangement of Geiger-Muller counters. The decay products were detected with a delayed coincidence technique. The results of the experiment were

- the charged particle emitted is an electron
- the average energy of the electron is greater than 25 Mev
- there is no evidence of emission of electrons with energy larger than 50 MeV.
- the shape of the energy spectrum of the electron excludes the possibility of being a single line

The conclusion was

*The average energy and the form of the energy spectrum of decay electrons are, within the accuracy of theory and experiments, in agreement with theoretical expectations of a process*

$$\mu \rightarrow e + \nu + \nu$$

*Universality*

The similarity of e-N and $\mu$-N interactions later known as Universality was for the first time pointed out by BP. In 1946 a paper of Conversi, Pancini and Piccioni [30] was published on the results of the behaviour of the negative and positive particles of the hard component of cosmic rays. This experiment showed that negative particles
where not captured when stopped in light elements as was expected if the negative particle had been the Yukava particle. Lattes, Occhialini and Powell [31] in 1947 in fact showed that cosmic ray muons were the decay products of a particle now known as $\pi$. Thinking about the Conversi experiment, BP made some relevant considerations as shown in the letter he wrote to Giancarlo Wick in 1947. letter to GC Wick [16]

Deep River 8 maggio 1947,

Caro Giancarlo ... se ne deduce una similarita’ tra processi beta e processi di assorbimento ed emissione di mesoni, che, assumendo non si tratti di una coincidenza, sembra di carattere fondamentale.

English translation

It can be deduced a similarity between beta processes and processes of absorption or emission of mesons, that, assuming that it is not coincidence, seems to be of fundamental character

He then published his considerations [17]

We notice that the probability ($10^8$ 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 beta-processes and processes of emission and absorption of charged mesons

This paper introducing the concept of Universality had not a large echo. In fact after 2 years there was a paper of G.Puppi that introduced the concept of a new fundamental force, the 'Universal weak interaction', [18] in which there was no reference to the Pontecorvo ideas. The same happened in the papers of other authors all concerning the universality of the weak interactions [19], [20], [21]

**Neutrino detectors**

In 1946 in his paper 'inverse beta processes ' [23] BP discussed the possibility of detection of neutrinos. Although the detection of the inverse beta decay

$$\nu + Z \rightarrow (Z - 1) + e^+$$

was at that time considered not possible. due the calculated cross section $10^{-44}cm^2$ given by Bethe and Peierls [25], the use of powerful neutrino sources as the nuclear reactors could make the detection of the above process possible. He wrote

*It is true that the actual $\beta$ transition is certainly not detectable in practice. However the nucleus of charge $(Z\pm1)$ produced in the reaction may be radioactive*
with a decay period well known. The essential point in this method is that the radioactive atoms produced must have different chemical properties of the irradiated atoms. Consequently it may be possible to concentrate the radioactive atoms from a very large volume.

The principal requirements for the irradiated material had to be

- the irradiated material must be not too expensive
- the produced nucleus must be radioactive with a period of at least one day, because of the long time involved in the separation
- The separation of radioactive atoms must be relatively simple
- the background must be as small as possible

BP suggested the reaction

$$\nu + ^{37}Cl \rightarrow ^{37}Ar + e$$

As a source of neutrinos he suggested
a) neutrino flux from the sun
b) neutrinos from recently developed nuclear reactors

It must be noted that the sun produces neutrinos, while in reactors antineutrinos are produced, at that the difference between neutrinos and antineutrinos was not yet clear.
The above process was used in the solar neutrino Homestake Davis experiment that started in 1962. The neutrino deficit compared with the prediction of the standard solar model gave origin to the "neutrino puzzle". The final result of the experiment, that lasted several decades, were published in 1998 [24]. In this paper the Pontecorvo suggestion was recognized.

In 1946 the detection of the inverse beta decay process

\[ \bar{\nu} + p \rightarrow n + e \]

with neutrinos from nuclear plants was not feasible. The development of the liquid scintillator technique ten years later allowed the detection of the above process.[26].

The Reines experiment was the first experimental proof of the existence of the neutrino.

Proportional counters
BP together with Hanna and Kirkwood developed a new technique of proportional counters, based on very large amplification in the gas. Sensitivity to a few ion couples was reached [27]. This development was essential in the solar neutrino Davis experiment and later in the He\(^3\) proportional counters of the SNO experiment.

The new technique was used in experiments of low energy spectrometry and used in the measurement of the tritium \(\beta\) spectrum.
In the experiment, published in 1949, a first measurement of the neutrino mass was obtained [28]. The obtained value was $m_{\nu} \leq 500$ eV.

### 0.4.2 Activities in Dubna

In 1950, BP started his activity in the Dubna laboratories (JINR). His notes and reports were in Russian. The English translation of part of this material can be found in Selected Scientific Works recollection on Bruno Pontecorvo [29]. He participated in experiments at the Dubna and Serpukov accelerators.

Out of the experiments at the Dubna Synchrocyclotron we can recall

- muon capture [32]
- measurement of the pion interactions [33]
- search for the production of $\Lambda$ in proton interactions at 700 MeV [35].
- search for anomalous scattering of muon neutrinos by nucleons [34].

Results of experiments at the Serpukhov accelerator can be found in [36], [37].
There are several arguments that he considered. We will give a brief resume. (One of the more important contribution of Pontecorvo, Oscillations, will be considered in next section [0.5])

**Neutrino beams**

In 1959 BP started to think to the possibility of performing experiments with neutrino produced at accelerators. The first problem to be solved was the possibility of the existence of two types of neutrinos, namely neutrinos from beta decay and neutrinos from pion and muon decay. He discussed the problem in [38]. One year later M. Schwarz discussed the same problem [39]. Schwarz then participated in an experiment at the AGS in Brookhaven USA together with L. Lederman and J. Steinberger. They proved that there are two type of neutrinos [40] named $\nu_e$ and $\nu_\mu$. For this result the three authors were awarded the Nobel prize in 1988. BP also proposed a non conventional technique to produce neutrino beams.

Conventional high energy neutrino beams are produced by pion and K decays produced in proton interactions. Their flavor content is: neutrinos (antineutrinos) coming from the decay of $(\pi, K)^+$ and $(\pi, K)^-$. These beams have a small $\nu_e$ contribution coming from the three body decay of K mesons. Bruno’s innovative idea was the ”beam dump” [42], a technique proposed to search for
short lived particles that decay before interacting. Protons are made to interact in heavy materials. Pions and kaons interact before decaying, so the only produced neutrinos come from the decay of short lifetime particles (charms). In this case the contribution of $\nu_e$ and $\nu_\mu$ are comparable.

**Neutrino and astrophysics**

Pontecorvo published several papers on this argument. Many of these are given in the following table.

| n | year | title                                                        | refer |
|---|------|--------------------------------------------------------------|-------|
| 1 | 1959 | Universal Fermi interactions and astrophysics               | 44    |
| 2 | 1961 | Neutrino and density of matter in the Universe              | 45    |
| 3 | 1963 | Neutrino and its role in Astrophysics                       | 46    |
| 4 | 1969 | Neutrino Astronomy and lepton charge                        | 47    |

All these papers can be found translated in English in ref [29]

## 0.5 Oscillations

The contribution of Bruno Pontecorvo to the field of neutrino oscillation was fundamental and he defended the concept of oscillations in years in which the neutrino were considered massless and so oscillation impossible. In this section we will present
• Basics of neutrino oscillation theory
• Experimental results
• The Bruno Pontecorvo contribution

0.5.1 Basics of neutrino oscillation theory

As in the quark sector the weak interactions states are a linear superposition of the mass eigenstates. These states are connected by an unitary matrix $U$

$$\nu_\alpha = \sum_j U_{\alpha j} \cdot \nu_j$$

with index $\alpha$ running over the three flavor eigenstates and index $j$ running over the three mass eigenstates. The matrix $U$ is called the Pontecorvo–Maki–Nakagawa–Sakata. In the general case, a $3 \times 3$ matrix can be parametrized by 3 mixing angles $\theta_1 = \theta_{12}$, $\theta_2 = \theta_{23}$, $\theta_3 = \theta_{13}$ and a CP violating phase $\delta$. A frequently used parametrization of the $U$ matrix is the following

$$U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{+i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}$$

where $c_{jk} = \cos(\theta_{jk})$ and $s_{jk} = \sin(\theta_{jk})$. 

21
Given three neutrino masses, we can define two independent square mass differences $\Delta M_{12}^2$ and $\Delta M_{23}^2$. $\Delta M_{12}^2 = M_1^2 - M_2^2$, $\Delta M_{23}^2 = M_2^2 - M_3^2$

It has experimentally been shown that $|\Delta M_{12}^2| \ll |\Delta M_{23}^2|$ and so $\Delta M_{13}^2 \simeq \Delta M_{23}^2$.

The mass spectrum is formed by a closely spaced doublet $\nu_1$ and $\nu_2$, and by a third state $\nu_3$ relatively distant.

In many cases oscillations can be studied considering the simplified approximation of two family mixing. With two mass states $M_1$ and $M_2$, the mixing matrix is reduced to $2 \times 2$ and is characterized by a single parameter, the mixing angle $\theta$ (omitting irrelevant phase factors):

$$
\begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
$$

Consider for example a $\nu_e$ beam and $\nu_e \to \nu_\mu$ oscillations

At a distance $L$ from the source the probability of detecting a $\nu_e$ as $\nu_\mu$, is

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta) \sin^2(\Delta M^2 L/4E)$$

where $\Delta M^2 = M_1^2 - M_2^2$. Choosing to express $\Delta M^2$ in $eV^2$, $L$ in m(Km) $E$ in MeV(Gev) we have

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta) \sin^2(1.27\Delta M^2 L/E)$$
we emphasize that oscillations are sensitive only to the
difference of the square masses.

0.5.2 Experimental results. Solar neutrinos

Radiochemical experiments
The experimental story of the oscillations started with the
solar neutrino 'puzzle'. The flux of neutrinos coming from
the sun, as detected in the Homestake neutrino detector,
was below the expected one. Nuclear reactions in the Sun
giving rise to neutrinos start with the PP reaction

\[ p + p \rightarrow H^2 + e^+ + \nu_e \]

neutrinos produced in this reaction constitute 99% of all
neutrinos emitted by the sun. The energy spectrum
of neutrinos has an end point at 0.42 MeV. Additional
neutrinos are emitted in the chain process initiated by
the PP reaction

\[ H^2 + p \rightarrow He^3 + \gamma \]
\[ He^3 + He^4 \rightarrow Be^7 + \gamma \]
\[ Be^7 + e^- \rightarrow Li^7 + \nu_e \]
\[ Be^7 + p \rightarrow B^8 + \gamma \]
\[ (Be^8)^* \rightarrow 2He^4 B^8 \rightarrow (Be^8)^* + e^+ + \nu_e \]

The net result of the chain is

\[ 4p + 2e^- \rightarrow He^4 + 2\nu_e + \gamma. \]
The Q of the reaction is 26 MeV and the neutrinos take away on the average 0.5 MeV.

In the Davis experiment solar neutrinos coming from the sun were detected via the reaction

$$\nu_e + Cl^{37} \rightarrow Ar^{37} + e$$

as suggested by BP.

The Davis detector was a large tank containing 100000 gallons of tetrachloroetilene. It was located in the Homestake mine at a depth of 4800 meters.

Using physical and chemical methods the amount of produced $Ar^{37}$ was extracted from the target material. The $Ar^{37}$ is unstable, so the extraction had to be performed periodically Auger electrons or photons emitted in the decay were detected in proportional counters.

The experiment ran from 1970 to 1995 and the results were compared with the model of neutrino emission from the sun the Standard Solar Model (SSM) The main contributor to the computation of SSM model and of his results was J.Bahcall \[55\]. The final result of the experiment was

$$\Phi(Davis)/\Phi(SSM) = 0.34 \pm 0.04$$

Although final results were published in 1998 \[24\], preliminary were published before, see for example \[56\].
The disagreement between SSM and results, the ‘solar neutrino puzzle’ was largely discussed in the physics community and many explanations were given, but only BP indicated oscillations as the origin of the discrepancy. Following the Davis results other experiments were done. The Gran Sasso Laboratories (Italy) experiment Gallex \cite{59} and then GNO \cite{60} and Baksan (Russia) \cite{58} radiochemical experiments studied the process

$$\nu_e + Ga^{71} \rightarrow Ge^{71} + e^-$$

The threshold of this reaction is 0.223 Mev so it is sensitive to the PP reaction that has an energy endpoint at 0.42 Mev while the Chlorine experiment had a threshold of 0.813 Mev and therefore was not sensitive to the PP reaction that is the origin of the the large majority of solar neutrinos.

The weighted average of all Gallium results is \cite{57}

$$Capture\ Rate = 67.6 \pm 3.71 \ SNU$$

to be compared with the prediction of 128 of the SSM (1 SNU (standard neutrino unit) = \(10^{-36}\) neutrino captures/(atom sec)).

Real time experiments

In the Kamioka mine in Japan the experiment Kamiokande ran from 1983 until 1988 followed by the Superkamiokande one, that started in 1996, and is still running.
Both experiments were large water Cherenkov counters (Kamiokande 3 ktons, Superkamiokande 50 ktons) in which the Cherenkov light emitted by fast particles is collected by photomultipliers. Solar neutrinos were detected via the reaction

\[ \nu_x + e \rightarrow \nu_x + e \]

all neutrinos contribute to the reaction but the main contribution is given by \( \nu_e \) because in this case we can have both charged current (CC) interaction and neutral current (NC) ones, while in the case of \( \nu_\mu \) and \( \nu_\tau \) only neutral current reactions are allowed. The ratio is CC/NC\( \approx 6 \)

Results of the experiment still confirming the neutrino deficit are
Kamiokande [61] flux

\[ 2.80 \pm 0.019(stat.) \pm 0.33(sys).10^6 cm^{-2} sec^{-1} \]

ratio \( \Phi(\nu_x)/\Phi(SSM) = 0.55 \pm 0.19 \pm 0.33 \)
Superkamiokande [62] flux

\[ 2.35 \pm 0.02(stat.) \pm 0.08(sys).10^6 cm^{-2} sec^{-1} \]

ratio \( \Phi(\nu_x)/\Phi(SSM) = 0.47 \pm 0.04 \pm 0.14 \)

The Superkamiokande result refer to phase 1 of the experiment. New results have been published [63] confirming the above results.
Confirmation of the oscillation hypothesis

The results on the ratio given above rely on the correctness of the SSM and so the interpretation of the value of the ratio as due to oscillations needs confirmation. The confirmation came in the year 2003 ’annus mirabilis’ from two experiments, SNO and Kamland.

The SNO experiment [64], Sudbury Neutrino observatory, was a 1000 tons heavy water Cherenkov detector. In Deuterium the following three reactions were observed:

1) $\nu_e + d \rightarrow p + p + e^-$ charged current interaction accessible only to $\nu_e$

2) $\nu_x + d \rightarrow p + n + \nu_x$ neutral current interaction accessible to all neutrinos. This is an unique feature of the SNO experiment that allows a direct verification of the SSM.

3) $\nu_x + e \rightarrow \nu_x + e$ accessible to $\nu_e$ and, with smaller cross section, to $\nu_\mu$ and $\nu_\tau$.

Reactions 1 and 3 were observed via the detection of the Cherenkov light emitted by electrons, while reaction 2 was detected via the observation of the neutron in the final state. Various neutron detection techniques were used in successive parts of the experiment. The results were summarized in the following way

$$R_{ee} = \frac{\Phi(CC')}{\Phi(NC')} = \frac{\Phi(\nu_e)}{\Phi(total)} = 0.34 \pm 0.023^{+0.029}_{-0.031}$$

The $\nu_e$ flux is depressed, in agreement with the results of
all solar experiments
\[ \Phi(\nu_x)/\Phi(\text{SSM}) = 1 \pm 0.1 \]
this is the fundamental result of the experiment.
The flux of all types of neutrinos is in good agreement with the SSM which is therefore confirmed.
Because the $\nu_e$ are depressed this means that neutrinos in their path from Sun to Earth have changed their flavor.
The Kamland experiment
The detector is located in the Kamioka mine in Japan. It consists of 1 kton scintillator contained in a balloon viewed by photomultipliers. 53 nuclear reactors surround Kamland at an average distance of 150 km. Emitted anti neutrinos interact in the hydrogen of the scintillator
\[ \bar{\nu}_\mu + p \rightarrow n + e^+ \]
The reaction products are detected as a pulse delayed pair, the first pulse being due to the annihilation of the positron, the second to delayed gammas emitted in the capture of the moderated neutron. This is the same technique used in the first detection of free neutrinos and in all $\bar{\nu}_e$ reactor neutrinos detection experiments. The survival probability, ie the probability that antineutrinos originated in the reactors reach the detectors has been computed to be
\[ 0.658 \pm 0.044 \text{stat} \pm 0.047 \text{syst} \]
Interpreting this result in terms of oscillations one obtains the same parameters that have been found in the analysis of solar neutrinos. A global two flavor analysis of Kamland data and solar data \cite{65} gives

\[ \Delta M^2 = (7.9^{+0.6}_{-0.5}) \times 10^{-5} \text{eV}^2 \]

\[ \tan^2 \theta = 0.40^{+0.10}_{-0.07} \]

This is another proof of the interpretation of solar neutrino deficit in terms of oscillation. After the results of these two experiments, neutrino oscillations from a possible theory become a well defined physical phenomenon.

0.5.3 Experimental results. Atmospheric neutrinos

While the observation of solar neutrinos concerns the disappearance of $\nu_e$ and so the (1,2) mixing parameters, information on the (2,3) mixing comes from the study of atmospheric $\nu_\mu$ disappearance experiments. Neutrinos are generated by the decay of hadrons produced by primary cosmic rays in the upper part of the atmosphere. $\nu_\mu$ are produced by the decay of pions and kaons while the $\nu_e$ are produced together with $\nu_\mu$ by the decay of muons. Many underground experiments have been made, the one
that has given a definite proof of disappearance of $\nu_\mu$ is the Superkamiokande experiment that used the same detector used for solar neutrinos. While the $\nu_e$ behave according to Montecarlo computations a clear deficit of upward $\nu_\mu$ ie from $\nu_\mu$ that have traversed the Earth was observed. The experiment studied the double ratio $R = (\mu/e)_{data}/(\mu/e)_{MC}$ that should be 1 in the absence of oscillations and that turned out to be $66$

$$R = 0.658 \pm 0.016 \pm 0.035$$

Indications of the upward $\nu_\mu$ deficit have been obtained also in other underground detectors $67$ and $68$. A direct proof of disappearance of muon neutrinos has been obtained in two long baseline experiments K2K $69$ and Minos $70$. These experiments utilize a two detector scheme. The distance between the two detectors and the energy of the beams are chosen to access the $\Delta M^2$ region given by the SK result. The results of the three experiments, either with atmospheric or with accelerators, given in the following table, are in good agreement and this fact is again a proof of the interpretation of results in terms of oscillations. All these experiments are disappearance experiments, the possibility of $\nu_\mu \rightarrow \nu_e$ is excluded by the SuperK result in which $\nu_e$ are in good agreement
| experiment | $\Delta M^2 \cdot 10^{-3}$ eV$^2$ | $\sin^2 2\theta$ |
|------------|-------------------------------|-----------------|
| ATMO SK [66] | 1.5-3.4 | $\geq 0.92$ |
| K2K [69] | 1.5-3.9 | $\geq 0.58$ |
| MINOS [70] | $2.38 \pm 0.2$ | $\geq 0.98$ |

Table 1: limits on the 23 mixing parameters

with the expectations and by the result of the Chooz reactor experiment so that the only possibility left is the $\nu_\mu \rightarrow \nu_\tau$ but no direct evidence of this reaction has been until now given. The Opera experiment [71] from CERN to LGNS will look for the appearence of $\tau$ produced by $\nu_\tau$ interactions. The difficulty, given the short lifetime of $\tau$, of detecting $\nu_\tau$ will be addressed using the high granulariy of nuclear emulsions.

0.5.4 The contribution of Bruno Pontecorvo

As it has been shown in the section 0.4.1 Pontecorvo suggested the possibility of measuring the reaction

$$\nu + Cl^{37} \rightarrow Ar^{37} + e$$

and as source of neutrinos he suggested solar neutrinos. The solar neutrino Davis experiment started the 'neutrino puzzle' and the originality of the BP contribution was largely acknowledged.

In 1957 R.Davis was doing the same experiment at the Savannah river reactor using $\overline{\nu}_e$. a rumor reached B.P in
Dubna, that the process had been observed. The rumour was false and Davis obtained a null result thus showing a difference between neutrinos and antineutrinos. The process
\[
\bar{\nu}_e + Cl^{37} \rightarrow Ar^{37} + e
\]
does not conserve leptonic number, so he started to think to processes that violate leptonic number and that the reason that the reaction did happen was the transition \(\nu_e \rightarrow \bar{\nu}_e\) in vacuum. He published two fundamental papers in 1957:
1)’Mesonium and anti-mesonium’, The conclusion of the paper was [48] .. *if the conservation of neutrino charge took no place the neutrino antineutrino transition would be in principle possible.*
2)’Inverse beta processes and non conservation of lepton charge’ [49]

*In the hypothesis of non conservation of neutrino charge a beam of neutral leptons from a reactor which at first consists mainly of antineutrino will change its composition at a certain distance from the reactor*

We note that this effect has been observed in the Kamland experiment.

At that time only one type of neutrinos was known. After the discovery of two types of neutrinos BP extended this concept to flavour oscillations [50].
In 1967 BP published a paper ‘neutrino experiments and the question of lepton charge conservation’ [41] in which he, given the evidence for $\nu$ and $\overline{\nu}_\mu$ difference, gave examples of processes that could test the leptonic charge conservation.

BP was very interested on the oscillation problem, many times in collaboration with S. Bilenky. He published several papers on solar neutrinos [52], [51], [53], [54]. In the last paper he explained the result of the Davis experiment in terms of oscillations. He wrote:

*It appears that the explanation in terms of neutrino mixing is much more attractive and natural than other explanations*

### 0.5.5 Present knowledge of the Pontecorvo-Maki-Nakagawa-Sakata matrix

As shown in the chapter on the neutrino oscillation theory the mixing matrix $U$ contains 3 angles and possibly a CP violating term $\delta$. The angles $\theta_{12}$ and $\theta_{23}$ are reasonably well known while for $\theta_{13}$ only upper limits are given, the more stringent has been given by the Chooz Experiment [72]; the phase $\delta$ is unknown. The determination of $\theta_{13}$ is very important because a not too small value of this quantity will open the possibility of the phase $\delta$ of CP violation in the neutrino field to be measured. Exper-
periments have been proposed and are in preparation, T2K [74] will look in a neutrino beam from Jaeri Japan to Superkamiokande through the detection of the subdominant $\nu_\mu \rightarrow \nu_e$ reaction. The reactor experiment DayaBay [75] will try to improve the limit on $\nu_e \rightarrow \nu_x$ of Chooz by a factor 10.
Appendix
Basics of neutrino oscillation theory
As in the quark sector the weak interactions states are a linear superposition of the mass eigenstates. These states are connected by an unitary matrix $U$

$$\nu_\alpha = \sum_j U_{\alpha j} \cdot \nu_j$$

with index $\alpha$ running over the three flavor eigenstates and index $j$ running over the three mass eigenstates.

The matrix $U$ is called the Pontecorvo–Maki–Nakagawa–Sakata. In the general case, a $3 \times 3$ matrix can be parametrized by 3 mixing angles $\theta_1 = \theta_{12}, \theta_2 = \theta_{23}, \theta_3 = \theta_{13}$ and a CP violating phase $\delta$. A frequently used parametrization of the $U$ matrix is the following

$$U = \begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix} \begin{pmatrix}
c_{13} & 0 & s_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13} e^{+i\delta} & 0 & c_{13}
\end{pmatrix} \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}$$

where $c_{jk} = \cos(\theta_{jk})$ and $s_{jk} = \sin(\theta_{jk})$.

Given three neutrino masses, we can define two independent square mass differences $\Delta M^2_{12}$ and $\Delta M^2_{23}$: $\Delta M^2_{12} = M^2_1 - M^2_2$, $\Delta M^2_{23} = M^2_2 - M^2_3$.

It has experimentally been shown that $|\Delta M^2_{12}| \ll |\Delta M^2_{23}|$ and so $\Delta M^2_{13} \simeq \Delta M^2_{23}$.

The mass spectrum is formed by a closely spaced doublet $\nu_1$ and $\nu_2$, and by a third state $\nu_3$ relatively distant.

In many cases oscillations can be studied considering the simplified approximation of two family mixing. With two mass states $M_1$ and $M_2$, the mixing matrix is reduced to $2 \times 2$ and is char-
acterized by a single parameter, the mixing angle $\theta$ (omitting irrelevant phase factors):

$$\begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}$$

Consider for example a $\nu_e$ beam and $\nu_e \to \nu_\mu$ oscillations. At a distance $L$ from the source, the probability of detecting a $\nu_e$ as $\nu_\mu$, is

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta) \sin^2(\Delta M^2 L/4E)$$

where $\Delta M^2 = M_1^2 - M_2^2$. Choosing to express $\Delta M^2$ in eV$^2$, L in m(Km) E in MeV(Gev) we have

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta) \sin^2(1.27 \Delta M^2 L/E)$$

we emphasize that oscillations are sensitive only to the difference of the square masses.

0.6 References
Bibliography

[1] W. Pauli, On the earlier and more recent story of neutrino. The English translation of the original paper can be found in Neutrino Physics edited by K. Winter pg 1

[2] J. Chadwick, Possible existence of the neutron. Nature 129,798,1932

[3] A. Vogel and A. Piepke, Review of particle physics: Introduction to neutrino properties. Physics Letters 667,517, 2008.

[4] E. Fiorini, Double $\beta$ decay and Majorana neutrinos. Twelfth International workshop on neutrino telescopes 459, 2007.

[5] H. V. Klapdor-Kleingrothous et al, Evidence for neutrinoless double beta decay. Mod. Phys. Lett. A16,2409,2001.

[6] G.W Rodeback and J.S.Allen, Neutrino recoil following the capture of orbital electrons in $A^{37}$. Phys. Rev. 86,446,1952

[7] F. Reines and C.L.Cowan, Detection of free antineutrino Phys. Rev. 117,159,1960

[8] F. Reines and C.L.Cowan, Proposal to detect free antineutrino Phys. Rev. 90,492,1953
[9] F. Reines and C.L.Cowan, Detection of free antineutrino. *Phys. Rev.* 92,830,1953

[10] M. Apollonio et al, Search for neutrino oscillations. *Europhys J. C* 27,331,2003

[11] E.Fermi, E.Amaldi, B.Pontecorvo, F.Rasetti, E.Segre, Influence of Hydrogenous substances in the radioactivity produced by neutrons I. *Ricerca scientifica* 5,282,1934

[12] E.Fermi, B.Pontecorvo, F.Rasetti, Influence of Hydrogenous substances in the radioactivity produced by neutrons II. *Ricerca scientifica* 5(2),280,1934

[13] B. Pontecorvo, Recent experimental results in nuclear Isomerism. B. Pontecorvo *Nature* 144, 212,1939

[14] B.Pontecorvo, Neutron well logging. A new geological method based on nuclear physics *Oil and gas journal* 40,32,1941, ref [29] p17

[15] G.P. Hincks and B. Pontecorvo, On the disintegration products of the 2.2 μsec meson, *Phys. Rev.* 77,102,150

[16] Fondo Wick. Archivio Scuola Superiore Normale di Pisa

[17] B.Pontecorvo, Nuclear capture of mesons and meson decay. *Phys. Rev* 72,246,1946

[18] G.Puppi, Mesoni dei raggi cosmici, *Nuovo Cimento* 5,587,1948

[19] O. Klein, Mesons and nucleons, *Nature* 161, 897,1948

[20] T.D. Lee, M.Rosenbluthamd C.N.Yang, Interactions of Mesons with nucleons. *Phys. Rev* 75,905,1949
[21] J.Tiomno and J.A. Wheeler, Energy spectrum of electrons from muon decay. *Rev. Mod. Phys.* 21,144,1949

[22] V.P.Dzelepov, The genius of Bruno Pontecorvo, ref [29] pg 487

[23] B. Pontecorvo, Inverse beta processes *Chalk River Report*, Pd-205,1946

[24] B.T. Cleveland et al, Measurement of the solar neutrino flux with the Homestake neutrino detector *Astrophysica journal* 496,505,1998

[25] H.Bethe and R. Peierls, The Neutrino *Nature*133,689,1934

[26] F. Reines et al, Detection of free neutrinos *Phys Rev* 117,159,1960

[27] G.C. Hanna,D.H.W. Kirkwood and B. Pontecorvo, High multiplicity proportional counters for energy measurements *Phys Rev* 75,985,1949

[28] G.C. Hanna,D.H.W. Kirkwood and B. Pontecorvo, the beta spectrum of He$^3$ *Phys Rev* 75,983,1949

[29] Editors: S. Bilenky et al, Selected Scientific Works, recollection on Bruno Pontecorvo *Societa Italiana di fisica* Bologna 1997

[30] M.Conversi,E.Pancini and O.Piccioni, On the disintegration of negative mesons, *Phys Rev.* 71,209,1947

[31] C.M.G. Lattes,G.P.S. Occhialini,C.F Powell, Observation of the tracks of slow mesons in photographic emulsions *Nature*160,453,1947
[32] O.A. Zaimidoroga et al, Measurement of the total muon capture rate in He-3  *Phys.Lett* 6,100,1963.

[33] I.V. Falomkim et al, Elastic scattering of pi+ and pi- on He-4 at 68 and 154 mev. *Nuovo Cim.* A21,168,1974. Elastic scattering of pi+ and pi- mesons on He-3 at 154 mev. *Nuovo Cim.* A24,93,1974.

[34] I.M. Vasilevsky et al, Search for anomalous scattering of muon neutrinos by nucleons *Phys.Lett* 1,345,1962.

[35] M.P Balandin et al, The possibility of the formation of Λ0 particles by protons with energy up to 700 Mev  *Z theor exp physics* 29,265,1955.

[36] A.V. Demyanov et al, Search for a new type of radioactivity in aluminum and tungsten targets irradiated by 70-gev protons,  *Yad.Fiz* 13,786,1971.

[37] A. M. Zaitsev et al, Search for metastables states with life time greater than 5 msec in Pb target irradiated with 60-70 GeV protons  *Yad.Fiz* 23,1190,1976

[38] B Pontecorvo, Electron and muon neutrinos  *Z theor exp physics* 37,1751,1959

[39] M. Schwartz, Possibility of using high energy neutrinos to study weak interactions  *Phys Rev lett* 4,307,1960

[40] G.Damby et al, The observation of high energy interactions. The existence of two type of neutrinos.  *Phys Rev lett* 9,36,1962
[41] B. Pontecorvo, Neutrino experiments and the question of leptonic charge conservation. *Z. theor Exp. Physics* 53,1717,1967 ref [29] pg 249

[42] B. Pontecorvo, Direct production of neutrino and charmed particles. *Z. theor Exp. Physics* 69,452,1975

[43] Tagging direct neutrinos. A first step in neutrino tagging. B. Pontecorvo, *Lettere Nuovo Cimento* 25,257,1979

[44] B. Pontecorvo, Universal Fermi interactions and astrophysics, *Z. theor Exp. Physics* 36,1615,1959 [29] pg 169

[45] B. Pontecorvo, Ya. Smorodinski, The neutrino and density of matter in the universe. *Z. theor Exp. Physics* 41,239,1961, ref [29] pg 186

[46] B. Pontecorvo, The neutrino and its role in astrophysics, *Uspekh Fiz. Nauk* 79,3,1963 ref [29] pg 212

[47] V. Gribov, B. Pontecorvo, Neutrino astronomy and lepton charge. *Phys. Lett.* 28b,493,1969 ref [29] pg 263

[48] B. Pontecorvo, Mesonium and anti-mesonium. *Sov. Phys. JETP*, 6:429,(Zh. Eksp. Teor,33,549,1957), 1957.

[49] B. Pontecorvo, Inverse beta processes and nonconservation of lepton charge. *Sov. Phys. JETP*, 7:172–02, (Zh. Eksp. Teor. fiz,34,247,1957), 1958.

[50] S. Bilenky, B. Pontecorvo, Lepton mixing and neutrino oscillations. *Phys rep* 41,225,1978 (Zh. Eksp. Teor. fiz,34,247,1957)
[51] S.M. Bilenky, B. Pontecorvo, Lepton Mixing and the solar neutrino puzzle. *Comments Nucl part Phys* 7, 149, 1977 ref [29] pg 353

[52] S. M. Bilenky, B. Pontecorvo, Reactor experiments and solar neutrino experiments. *Lettere Nuovo Cimento* 43, 786, 1986

[53] S. M. Bilenky, B. Pontecorvo, Discussion Of The Solar Neutrino Problem In the light Of Reactor Neutrino Oscillation Experiments. *Sov.J.Nucl.Phys.* 43:786, 1986

[54] B. Pontecorvo, Lepton mixing and solar neutrino puzzle. *Dubna Report* E10545, 1977

[55] J.N. Bahacall, solar models: an historical overview. *Nuclear physics B (proc suppl)* 118, 77, 2003

[56] J.N. Bahacall, R. Davis, Solar neutrinos: a scientific puzzle. *Science* 191, 264, 1976

[57] B.T. Cleveland V. N. Gavrin, radiochemical neutrino experiments. *electronic preprint* nucl-ex/0703012, page 8, 2007.

[58] W.J.N. Abdurashitov et al, Measurement of neutrino capture rate in metallic gallium. *Phys. Rev. C*, 60:0055801–3

[59] W. Hampel et al, Gallex solar neutrino observation, *Phys. Lett. B*, 447, 127, 1999.

[60] W. Altmann et al, Complete results of five years of GNO solar neutrino observations. *Phys. Lett. B*, 616, 174, 2005.

[61] S. Fukuda et al, Solar neutrino data covering solar cycle 22. *Phys.Rev Lett* 77, 1683, 1996

42
[62] J. Hosaka et al, Solar neutrino measurements in superkamiokande-I Phys.Rev.D 73,2001,2006

[63] J.P. Cravens et al, Solar neutrino measurements in superkamiokande-II Phys.Rev. D 78,032002,2008

[64] B. Aharmim et al, Determination of nue and total b-8 solar neutrino fluxes with the sudbury neutrino observatory,phase 1 data set. Phys. Rev. C 75,045502,2006

[65] T. Araki et al, Measurement of neutrino oscillations with kamland: Evidence for spectral distorsion. Phys. Rev. Lett. 94,08180, 2005.

[66] Y.Fukuda et al, Evidence for oscillations of atmospheric neutrinos. Phys. Rev. Lett 81:1562, 1998.

[67] M. Ambrosio et al, Measurement of atmospheric neutrino oscillations ,global analysis of data collected with the macro detector.

Euro Phys. Journal, 36:323, 2004.

[68] M. Sanchez et al, Measurement of l/e distribution in soudan2 and their interpretation as neutrino oscillations. Phys. Rev. D 68,1130042003,2003

[69] M.H. Ahn et al. Mesurement of neutrino oscillations by the k2k experiment. Phys. Rev D. , 74,072003, 2006.

[70] A. Blake et al, neutrino oscillation results from Minos. J.Phys.Conf.Ser .120,062027,2008

[71] M. Guler et al, OPERA Collaboration, Experiment proposal. CERN-SPSC-2000-028, 2000.
[72] M. Apollonio et al, Search for neutrino oscillations on a long base-line at the Chooz nuclear power station. *Eur. Phys. J.*, C27,331,2003

[73] F.Ardellier, Double Chooz, a search for neutrino mixing angle theta-13. *electronic preprint hep-ex/0606025*, page 173, 2006.

[74] K. Nishikawa, Status of j-park facility and the T2K experiment. *Twelfth International workshop on neutrino telescopes*, pages 197–4, 2007.

[75] Xineng Guo et al, A precise measurement of the neutrino mixing angle theta(13) using reactor antineutrinos at daya bay. *electronic preprint hep-ex/0701029*, page 162, 2007.
