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ON B. PONTECORVO CONTRIBUTIONS TO WEAK INTERACTION AND NEUTRINO PHYSICS

S.T. Petcov * †
Scuola Internazionale Superiore di Studi Avanzati,
and Istituto Nazionale di Fisica Nucleare, Sezione di Trieste,
I-34014 Trieste, Italy

Abstract

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† Permanent address: Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, BG-1784 Sofia, Bulgaria.

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S.T. PETCOV

Scuola Internazionale Superiore di Studi Avanzati, and

Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, I-34013 Trieste, Italy,

and

Institute of Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, 1784 Sofia, Bulgaria

ABSTRACT

The major contributions of B. Pontecorvo (1913–1993) in the field of neutrino physics and the studies of weak interaction are reviewed.

1 Introduction

Professor Bruno Pontecorvo was born in 1913 in Pisa (Italy). As is well known, he was formed as a physicist in the famous school of E. Fermi at the University of Rome. First as a student and later as a collaborator, B. Pontecorvo was a member of the Fermi group from 1931 to 1936. In that period he actively participated in the "discovery of slow neutrons" by E. Fermi et al. [1] For his contribution to the neutron studies B. Pontecorvo was awarded a fellowship which permitted him to work for four years at the Institute of Radium in Paris in the group of F. Joliot-Curie (1936-1939). His investigations of nuclear isomerism performed in Paris led to the discovery of the "nuclear phosphorescence". During his scientific career B. Pontecorvo made major contributions in various branches of elementary particle physics [2], but his results and ideas in the field of neutrino physics and weak interactions are the most significant. For this reason we shall review in what follows only what we consider to be the major contributions of B. Pontecorvo in the study of neutrinos and the weak interaction.

2 Radiochemical Methods of Neutrino Detection

Invented in 1946 by B. Pontecorvo [1], the radiochemical methods of neutrino detection, examples of which being the well-investigated and already exploited in solar

[1] See, for instance, E. Fermi, Collected Papers, The University of Chicago Press (Chicago, 1962), Vol. 1, pp. 683, 689, 693, 697, 761, 763, 765.

[2] It is not widely known, for example, that B. Pontecorvo suggested independently of A. Pais that kaons and hyperons are pair produced in strong interactions (ZETF 29 (1955) 140); this idea lead to the concepts of strangeness and its conservation in strong interactions.

neutrino astronomy Cl–Ar and Ga–Ge methods, are based on two essential points: i) in processes, generated by neutrino bombardment and corresponding to inverse β–decays, a stable nucleus (A,Z) is converted into a nucleus (A,Z+1) which in most cases is β–radioactive with a known decay period, and ii) the radioactive atoms produced by inverse β–decay processes have different chemical properties from the irradiated atoms. The latter makes it possible to concentrate the β–radioactive atoms, produced by interactions of neutrinos, from extremely large volumes irradiated by neutrinos. In [1] B. Pontecorvo formulated five criteria which the target and the produced nuclei should satisfy in order to be acceptable for radiochemical detection of neutrinos. These criteria are still valid today. The simplest (and the most inexpensive) radiochemical method of neutrino detection - the Cl–Ar method, was also proposed by B. Pontecorvo in [1]: it is based on the reaction $\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$; the produced ^{37}Ar undergoes a K–capture (half-life T $\cong$ 34 days), $^{37}Ar + e^- \rightarrow {}^{37}Cl^* + \nu_e$, and the $^{37}Cl^*$ thus formed emits (practically immediately) an Auger electron with an energy 2.8 keV ($^{37}Cl^* \rightarrow {}^{37}Cl + e^-$). It was pointed out in [1] that a convenient compound of Cl to use in a possible experiment is the carbon tetrachloride [3], CCl_4.

Thus, the method proposed by B. Pontecorvo in [1] consists in irradiation by neutrinos of extremely large volumes of a Cl compound for a period of about one month and in extraction of the radioactive ^{37}Ar simply by a physical method, in other words, without complicated chemistry. The ^{37}Ar must after that be introduced in a small counter having a registration efficiency close to 100% (because of the high yield of Auger electrons). It is important that there exist cheap, not too chemically active and not poisonous Cl compounds (e.g., CCl_4 or C_2Cl_4), and that the radioactivity of ^{37}Ar has a period T long enough to allow one to achieve a relatively effective separation [4].

The neutrino sources considered in [1] were: the Sun, a nuclear reactor during operation, and the "hot" uranium metal extracted from a nuclear reactor (or the fission fragment concentrate from "hot" uranium metal). Few comments are in order. In 1934 H. Bethe and R. Peierls, in a well-known article published in Nature (vol. 133, p. 689), estimated on the basis of the Fermi theory of β–decay the cross-section of neutrino interaction with matter and concluded that "there is no

[3] Carbon tetrachloride was used as a target in the reactor experiment of R. Davis [6]. The compound used in the solar neutrino experiment of Davis et al. [4,5] is perchlorethylene, C_2Cl_4.

[4] L. Alvarez, who in 1949 considered in greater detail the use of the Cl–Ar method for detection of reactor (anti) neutrinos, wrote: "... It is possible to justify the choice of ^{37}Ar as the radioactive substance. An examination of the isotope table shows that no other substance combines all the highly desirable features of ^{37}Ar, and in fact, no other isotope even comes close to being a worthwhile candidate for the experiment." (See L. Alvarez, University of California (Berkeley) Report No. UCRL-328, April 18, 1949, Berkeley. Incidentally, it is sometimes incorrectly stated in the physics literature that the Cl–Ar method was suggested by B. Pontecorvo (in [1]) and independently by L. Alvarez in the report just quoted. In his report L. Alvarez acknowledges that the Cl–Ar reaction for detection of neutrinos was proposed earlier by B. Pontecorvo, refers to the article by B. Pontecorvo and acknowledges at the end "helpful conversations", in particular, with B. Pontecorvo Let us add also that the six conditions for a given reaction to be feasible for radiochemical detection of neutrinos discussed by L. Alvarez in the quoted paper practically coincide with the five criteria formulated by B. Pontecorvo in ref. [1].)

practical possible way of observing the neutrino". B. Pontecorvo contested this view in [1]. He was the first to realise that the Sun and the nuclear reactors are powerful sources of neutrinos, that neutrinos can be detected, and, in particular, that they can be detected in experiments performed at reactors. As we all know, neutrinos were indeed observed first approximately ten years later by F. Reines and C. Cowan in an experiment performed at a nuclear reactor and conceived approximately six years after the original suggestion made in [1] by B. Pontecorvo.

The advantages of the Cl–Ar method listed above were fully recognized in several years and are presently rather well known. What is less widely known is that i) the Cl–Ar method possesses also a much more subtle advantage which was noticed first by B. Pontecorvo [2,3] two years after the method was proposed, and that ii) B. Pontecorvo made an important discovery [3] and a very significant contribution in the practical development of the Cl–Ar method (and, in general, of the radiochemical methods of solar neutrino detection) based on it [2]. Both are used in the Cl–Ar experiment of Davis et al. [4,5] (see also [6]) and in the Ga–Ge experiments [7,8] (SAGE and GALLEX), both are crucial for reducing the background in these experiments, and, in fact, ensure the success of the experiments [5]. More specifically, performing (with his colleagues from the Chalk River Laboratory) tests with ^{37}Ar for a future neutrino detector [6], B. Pontecorvo discovered [3,2] (independently of S. Curran et al. [9]) "the high gain gas amplification proportional counter regime" of the Geiger-Muller counters, in other words, a special regime of operation of the proportional counters. He recognized that this discovery is very important for the neutrino detection since it permits one to reduce considerably the effective background of the counters. Thus, B. Pontecorvo was the first to understand and to realise the essential necessity of using instead of ordinary Geiger-Muller counter a special type of proportional counter, the measurement of the pulse amplitudes of which must help in distinguishing the background from genuine decay events due to K–capture of the ^{37}Ar produced by neutrino irradiation of ^{37}Cl [7]. In this connection B. Pontecorvo entirely renewed the proportional counter technique and used it [2] to measure (first) L–capture in ^{37}Ar ($\sim$ 10 ion pairs). He was able to construct already in 1949 a proportional counter with an extremely low effective background [2] (for the neutrino detection through the Cl–Ar method [8] [11]), practically as low as in the present day counters used by R. Davis et al. [5], and by the SAGE [7] and GALLEX [8] collaborations. B. Pontecorvo suggested also that the form of the proportional counter pulses (more precisely, the rise-time of the pulses) in addition to their amplitude should be measured in order to decrease furthermore the effec-

[5] As follows from [1], B. Pontecorvo was well aware of the fact that the success in the use of the Cl–Ar method (or of any other radiochemical method) for neutrino detection will depend on the level of suppression of the various background processes, which could be achieved in a real experiment.

[6] The plans to build such a detector at the Chalk River Laboratory seem to have been abandoned in 1949 (see e.g., ref. [10]).

[7] The additional advantage of the Cl–Ar method referred to earlier represents the very specific height and form (see the text) which the pulse in the proportional counter (of Pontecorvo) has when generated by the 2.8 keV Auger electron, emitted following the K–capture in the ^{37}Ar. Let us add that the Ga–Ge method possesses similar advantages.

[8] That the proportional counter constructed by B. Pontecorvo can be especially useful for neutrino detection based on the Cl–Ar method was noticed first by L. Alvarez (see ref. [10], p. 42).

tive background of the counter [12] [9]. In his first neutrino experiment based on the Cl–Ar method (performed in 1955) R. Davis used a Geiger-Muller counter for the detection of ^{37}Ar [6]. The first results of the Cl–Ar solar neutrino experiment of R. Davis et al. [4] were obtained by using a proportional counter of the type constructed first by B. Pontecorvo in 1949 and the information about the amplitude of the pulses only. In these first runs "^{37}Ar activity was not observed over a counter background ..." and only an upper limit on the ^{37}Ar production rate due to solar neutrinos was set. Only after the information about the pulse form (i.e., rise-time) began to be used, which led to an additional considerable reduction of the effective background (by approximately a factor of 10 [14]) in the proportional counter practically to its minimum possible level (due to cosmic rays) at the location of the detector, a positive signal due to the solar neutrinos could be and was observed [10] [5]. This was the beginning of the measurement of the "high" energy part ($E \geq 0.816$ MeV) of the flux of neutrinos emitted by the Sun, performed by R. Davis with such remarkable success [11].

On the basis of the above we can conclude that the contributions of B. Pontecorvo to the foundation and the development of the Solar Neutrino Astronomy are fundamental. The first successful solar neutrino astronomy observations, performed by R. Davis and his collaborators are based on the Cl–Ar method proposed by B. Pontecorvo, on the use of the proportional counters for ^{37}Ar detection of the type developed by him, and on the specific experimental recognition "inventions" suggested by B. Pontecorvo on the basis of his detailed knowledge of the ^{37}Ar decay experimental signatures and permitting substantial reduction of the background to be achieved. Similar proportional counters and the same recognition "inventions" are being used also in the Ga–Ge experiments SAGE and GALLEX. Each one of these contributions is indispensable for the success of the Cl–Ar and the Ga–Ge experiments. The scientific significance of the results of these experiments is difficult to overestimate.

3 The Two Neutrino Hypothesis and Test, and Neutrino Physics at Accelerators

Another significant contribution to the study of the weak interaction and neutrinos, whose implications were fundamental for our current understanding of the existence of a family structure in the observed variety of leptons and quarks, was made by B. Pontecorvo in 1959 [17] (see also [18]). By 1959 interactions caused by reactor antineutrinos have been observed in the experiment of F. Reines and C. Cowan, which together with the results of the first Cl–Ar experiment of R. Davis [6] proved that the antineutrinos emitted in β–decay and the neutrinos emitted in electron capture are not identical. The two-component neutrino theory was formulated (by

[9] This is acknowledged, in particular, in ref. [13].

[10] In ref. [14] R. Davis writes (together with J. Bahcall) that the idea to use the pulse rise-time information for elimination of a considerable part of the background in the proportional counters used in the Cl–Ar experiment was suggested to him in 1970 by his colleague-astronomer G. Garmire .

[11] The Cl–Ar method of neutrino detection is sometimes called the Pontecorvo method (see, e.g. [15]) while the reaction $\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$ used for the registration of solar neutrinos by R. Davis was named, e.g., in [16] the Pontecorvo–Davis reaction.

L. Landau, T.D. Lee and C.N. Yang, and A. Salam) and was experimentally confirmed (by M. Goldhaber et al.). The universal (V-A) theory of the weak interaction was proposed approximately a year later (i.e., in 1958) by E.C.G. Sudarshan and R.E. Marshak, and by R. Feynman and M. Gell-Mann. This theory was aesthetically very appealing and there were strong experimental indications in favour of its validity. In those years it was universally supposed that the neutrino emitted in μ^-- capture (or together with μ^+ in the π^+- meson decay) is identical to the neutrino emitted in e^-- capture [12]. In their famous articles on the universal (V-A) theory of the weak interaction [22,23], for instance, neither E. Sudarshan and R. Marshak, nor R. Feynman and M. Gell-Mann even mention the possibility that the indicated neutrinos can be different particles [13]. In 1958 it was noticed [24] that if the two neutrinos under discussion were identical particles the processes $\mu^\pm \to e^\pm + \gamma$, $\mu^\pm + N \to e^\pm + N$, $\mu^\pm \to e^\pm + e^+ + e^-$, should exist. These processes were not observed. G. Feinberg calculated, in particular, the $\mu \to e + \gamma$ decay branching ratio within the intermediate vector boson theory and found that it exceeds at least by a factor of 5 the corresponding upper limit obtained experimentally [14]. He concluded that the "... intermediate meson theory is probably inconsistent with the experimental absence of the $\mu \to e + \gamma$ decay mode" [24].

In [17] B. Pontecorvo pointed out that there exists no experimental evidence whatsoever that the neutrino emitted in e^-- capture (ν_e) and the neutrino emitted in μ^-- capture (or $\pi^+ \to \mu^+ + \nu$ decay) (ν_μ) are the same particle. He noticed that the problem with nonobservation of the processes $\mu^\pm \to e^\pm + \gamma$, $\mu^- + N \to e^- + N$, $\mu^\pm \to e^\pm + e^+ + e^-$, can most naturally be resolved if the neutrino ν_e were different from the neutrino ν_μ. A very simple and ingenious experiment was proposed [17] to test the hypothesis that $\nu_e \neq \nu_\mu$. It was suggested to look in neutrino-nucleon interactions for production of $e^-(e^+)$ by neutrinos ν_μ (antineutrinos $\bar{\nu}_\mu$) originated in $\pi^+ \to \mu^+ + \nu_\mu$ ($\pi^- \to \mu^- + \bar{\nu}_\mu$) decay. A nonobservation of e^- (e^+), as was remarked in [17], would be a proof that $\nu_e \neq \nu_\mu$. One of the genuinely original elements of this proposal was the realization [17] (see also the first article quoted in ref. [18]) that beams of neutrinos ν_μ ($\bar{\nu}_\mu$) having sufficiently high intensities to perform studies of the weak interaction can actually be obtained at the high energy proton accelerators then being constructed, by making use of the copious yield of $\pi-$ mesons in the proton-nucleon collisions. The same idea was expressed by M. Schwartz seven months later [26] [15].

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[12] That the neutrinos emitted in the e^-- capture and in μ^-- capture can be different particles was certainly clear to some of the scientists who made the first studies of the muon properties (see, e.g., refs. [19-21]). We shall use in what follows the currently used notation for these neutrinos - ν_e and ν_μ , respectively, which was introduced by B. Pontecorvo in 1959 (see ref. [17]).

[13] It is interesting to note that at the same time R. Feynman and M. Gell-Mann made the following remark in their article [23]: "We deliberately ignore the possibility of a neutral current, containing terms like $(\bar{e}e)$, $(\bar{\mu}e)$, $(\bar{n}n)$, etc. and possibly coupled to a neutral intermediate field".

[14] Incidentally, B. Pontecorvo first (and as early as in 1947) realized the importance of the studies of the $\mu \to e + \gamma$ decay for understanding the properties of the $\mu-$ meson [19], performed the first experimental search for this decay, and obtained the first significant upper limit on the $\mu \to e + \gamma$ decay rate [25].

[15] In a "Note added in proof" in [26] M. Schwartz refers to the article by B. Pontecorvo in the following way: "The author's attention has been called to a somewhat related paper which has just appeared: B. Pontecorvo, JETP 37 (1959) 1751".

The two-neutrino test proposed in 1959 by B. Pontecorvo was successfully carried out, as is well known, at the Brookhaven National Laboratory in 1962 by G. Danby, J.M. Gaillard, K. Goulianos, L.M. Lederman, N. Mistry, M. Schwartz and J. Steinberger [27]. The results of this experiment definitely proved that ν_e and ν_μ are different particles and thus established that leptons come in "doublets", each charged lepton possessing its own neutrino. The experiment of G. Danby et al., as envisaged by B. Pontecorvo and M. Schwartz and executed by L. Lederman, M. Schwartz, J. Steinberger and their collaborators, marked the beginning of the experimental studies with neutrino beams at accelerators, which proved to be remarkably fruitful in results enriching our basic knowledge about elementary particles: the discovery and the determination of the structure of the neutral current weak interaction, the detailed picture of the quark-gluon structure of the nucleon – just to mention two.

In 1988 L. Lederman, M. Schwartz and J. Steinberger were awarded the Nobel Prize in Physics "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino". All three scientists acknowledged the pioneer ideas of B. Pontecorvo which, in particular, led to the Brookhaven two-neutrino experiment: M. Schwartz and L. Lederman - in their lectures on the occasion of the presentation of the Nobel Prize [28] [16], and J. Steinberger - a few years earlier [29].

4 On the μ–Meson Properties and the Notion of the Weak Force

In the present section we shall review a paper by B. Pontecorvo from 1947 [19], remarkable both with the results obtained and the intuition demonstrated in it. This was the first of a sequence of papers by several different authors (O. Klein [30], G. Puppi [20], T.D. Lee, M. Rosenbluth and C.N. Yang [31], and J. Tiomno and J.A. Wheeler [21]) which led to the establishment of the notion of weak interaction as an independent fundamental interaction [32]. The first important step in this direction was the observation made by B. Pontecorvo in [19] that the β–decay, electron capture, and μ–capture are generated by one and the same universal interaction (i.e., the weak interaction).

By 1947 it was well understood that the β–decay and the electron capture were initiated by the same (β–decay) force, but no other manifestations of this force were known. The μ–meson (or the mesotron as it was called in 1947) was discovered in cosmic rays in 1937 and was universally thought to be the scalar particle proposed by Yukawa as a mediator of the nuclear force and of β–processes (i.e., β–decay and electron capture). The article by B. Pontecorvo of interest was inspired by the famous experimental result of M. Conversi, E. Pancini and O. Piccioni [33] who studied the decays of slow μ–mesons using iron and carbon absorbers. They discovered that the absorption rate of μ–mesons was relatively low, being approximately equal to 10^{-6} sec^{-1}, and that there were no visible tracks of particles after the muon was absorbed. B. Pontecorvo found in [19] that the rate of μ–capture by a nucleus is

[16] M. Schwartz, in particular, said: "Not long after this point we became aware that Bruno Pontecorvo had also come up with many of the same ideas we had. He had written up a proposed experiment with neutrinos from stopped pions, but he had also discussed the possibility of using energetic pions at a conference in the Soviet Union. His overall contribution to the field of neutrino physics was certainly major".

of the order of the rate of electron capture (when allowance is made for the difference in the disintegration energy and the difference in the volumes of the corresponding orbits from which the μ–meson and the electron are captured). In connection with the indicated result he wrote: "We assume that this is significant and wish to discuss the possibility of a fundamental analogy between the β–processes and the processes of emission or absorption of charged mesons".

B. Pontecorvo was acquainted with the article of E. Fermi, E. Teller and V. Weiskopf [34] in which it was shown that the mesotron cannot be the Yukawa particle supposed to mediate the nuclear force (otherwise its absorption rates in iron and carbon should have been, by at least ten orders of magnitude, larger that the rates observed). He was also aware of the fact that the observed properties of the mesotron are not compatible with the hypothesis that the mesotron mediates the β–decay. On the basis of these two facts a set of suggestions were made in [19], all very much to the point (as is clear today):

i) Since the mesotron cannot be identified with the Yukawa particle it need not be a scalar particle;

ii) The mesotron has spin 1/2;

iii) The mesotron decay is not a β–process in the sense that the mesotron does not decay into an electron and neutrino; rather it decays with emission of electron and two neutrinos, or of electron and photon, or in some other way;

iv) In the process of μ–capture a neutrino is emitted in the same way as in the process of electron K–capture.

As we know, all assumptions from the above list turned out to be correct [17], the only exception being the possibility of the mesotron decay into an electron and photon [18].

From 1947 to 1950 B. Pontecorvo realised (together with E. Hincks) a program of experimental studies of the mesotron properties the aim of which was to test the hypothesis i)-iii). B. Pontecorvo and E. Hincks were the first to show that the mesotron does not decay into electron and a photon [25], and among the first to obtain experimental evidences that the mesotron decays into electron and two other very light or zero mass particles (neutrinos) [39]. The second conclusion was based on the studies of the spectrum of electrons emitted in the μ–decay. In 1962 B. Pontecorvo performed (with a group of collaborators) an experiment [40] in which for the first time it was demonstrated that a neutrino is indeed emitted in the process of μ– capture.

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[17] The idea that the mesotron can have a spin equal to 1/2 was expressed in 1943 and published at the end of 1946 by S. Sakata and T. Inoue [35], who were among the first to realize the difficulties with the interpretation of the mesotron as a Yukawa particle. However, their article was not known to the physicists in Europe and in the United States in 1947. Even earlier, in 1941, the possibilities ii) and iii) (but not iv) !) were mentioned by L.W. Nordheim (see Phys. Rev. 59 (1941) 555).

[18] As was shown in the second half of the 70's (see refs. [36,37], as well as, e.g., the review article [38]), nonconservation of the lepton charges can appear naturally in the modern gauge theories of electroweak interaction, representing extensions of the standard theory. The processes $\mu \to e + \gamma$, $\mu \to 3e$, etc. are allowed in such theories, and can proceed with rates close to the currently existing experimental upper bounds. The searches of the $\mu \to e + \gamma$ decay (and of other lepton charge nonconserving processes) still continue today as its observation would be one possible manifestation of the supposed incompleteness of the standard theory of electroweak interaction (see, e.g., the latest edition of the Particle Data Group).

The significance of the article by B. Pontecorvo discussed above lies, in particular, in the fact that in it for the first time the idea of $\mu - e$ universality of the Fermi interaction was formulated [19], and the true nature of the muon was recognized. This idea, as expressed in [17], contained also the first hint of universal weak interaction. Let us add that the main physical concept of the 1947 idea of B. Pontecorvo concerns the existence of families of leptons and quarks. The profound reason for the observed family structure of the variety of leptons and quarks is still not understood today.

5 General Remarks

In the preceeding sections we have reviewed only what we consider to be the most significant contributions of B. Pontecorvo in physics. We did not discuss some of his results which are no less famous (and in some cases are, perhaps, even better known at present) and in fact, can turn out to be even more significant than those considered by us. In connection with this it is not an exaggeration to say that the ideas of B. Pontecorvo and his works are at the origin of what is usually called today "neutrino physics". They shaped the development of the neutrino physics from its birth in the fifties to its present mature state and continue to influence even the projects for future experiments in this field.

The Solar Neutrino Astronomy, whose foundations were laid in the 1946 article [1] by B. Pontecorvo, received a remarkable impetus in the second half of the 80's. At present three new experiments are in progress - Kamiokande III [41] (which in 1990 succeeded the Kamiokande II experiment [42]; the latter took data in the period 1986–1990), SAGE [7] (since 1989), and GALLEX [8] (since 1990) [20], and two second generation solar neutrino experiments - SNO [43] and Super Kamiokande [44], are under preparation. Two additional detectors – BOREXINO [45] and ICARUS [46], are at the stage of prototype tests, and the possibilities to build one more apparatus – the HELLAZ detector [47], which can be capable to measure, in particular, the spectrum of the lowest energy component of the solar neutrino flux (i.e., of the pp neutrinos) are being studied. New methods of neutrino detection (radiochemical as well as "real time") are under investigation [48], the ultimate goal being to solve the formidable problem of determining experimentally the fluxes and the spectra of the different components (pp, ^{7}Be, ^{8}B, etc.) of the total solar neutrino flux. All these experiments provide and will provide unique data about the physical conditions and the nuclear processes taking place in the deep interior of the Sun. These data are indispensable, in particular, for our understanding of stellar evolution. They also give information about the neutrino properties, which is impossible to obtain performing experiments at accelerators, reactors or meson factories (see below). Let us add that the program of experimental research in Solar Neutrino Astronomy extends well beyond the year 2000.

The experimental studies with neutrino beams, which began with the Brookhaven two-neutrino experiment [27] proposed by B. Pontecorvo, continued and still continue to be influenced by his ideas. The most well-known example is, perhaps,

[19] This is universally acknowledged at present (see, for example: Ch. Peyrou, Journal de Physique, 43 Suppl. C8 (1982), p. 24, and A. Pais, "Inward Bound", Oxford University Press, Oxford, 1986, p. 530).

[20] Both SAGE and GALLEX experiments exploit radiochemical methods of detection of solar neutrinos.

the numerous experimental searches for oscillations of neutrinos, i.e., transitions in flight between neutrinos of different types, say, ν_e ($\bar{\nu}_e$) and ν_μ ($\bar{\nu}_\mu$), which are being performed since the beginning of the 80's not only at accelerators, but also at reactors and meson factories.

In 1957 B. Pontecorvo considered [49] the problem of oscillations between muonium ($\mu^- e^+$) and antimuonium ($\mu^+ e^-$), and in particle physics in general, and came to the conclusion that oscillations can exist not only for bosons (e.g., between K^0 and $\bar{K}^0$), but also for electrically neutral fermions and, in particular, for neutrinos. Neutrino oscillations can take place if the states of the neutrinos produced in the weak interaction processes are not stationary, but rather are coherent superpositions of stationary states of neutrinos having different nonzero and, in general, small masses [49]. B. Pontecorvo did not see any compelling reason why neutrinos should be massless [21] and considered the possibility of existence of nonzero but small neutrino masses more attractive than the zero mass alternative. The basic question raised by B. Pontecorvo in ref. [49], in fact, is: are neutrinos drastically different (zero mass case) from, or quite similar (finite mass case) to the other known fermions. We still do not have a definite answer to this question, which can only be obtained by performing appropriate experiments [22].

In ref. [50] B. Pontecorvo pointed out the remarkable sensitivity of the neutrino oscillation experiments to small values of the neutrino masses [23], the reason being the interference nature of the oscillations. In the same article published in 1967 B. Pontecorvo discussed also i) neutrino oscillation experiments at reactors, accelerators and with cosmic rays, ii) the relation between the lepton number nonconserving reactions and decays and the flovour neutrino oscillations, iii) the concept of neutrino "sterility", and iv) the importance of neutrino oscillations for the interpretation of the results of the solar neutrino experiments [24]. Few remarks are in order in connection with iv). B. Pontecorvo was the first to raise the problem of the importance of neutrino oscillations in solar neutrino astronomy observations. He considered as rather natural the existence of a deficit of solar neutrinos due to oscillations of neutrinos. This was done in [50] before the first results of the experiment of R. Davis et al. have been obtained [4] and before the interpretation of the results of R. Davis et al. [5] led J. Bahcall and R. Davis to conclude that a deficit of solar neutrinos is indeed observed and to call this a "solar neutrino problem" [5,14]. The results of the Kamiokande, GALLEX and SAGE experiments reinforced the case for existence of solar neutrino deficit.

In 1969 B. Pontecorvo (with V. Gribov) formulated [51] the first phenomenological theory of the neutrino mixing and oscillations. Only the fields of the active neutrinos (ν_e and ν_μ) were used in the formulation [25], and the neutrinos with definite mass in the scheme proposed in [51] are Majorana particles. The indicated theory was extended to include also sterile (right-handed) neutrino fields in 1976 by S.M. Bilenky and B. Pontecorvo [53]. Both in [51] and in [53] the neutrino mixing was

[21] Let us add that no profound principle forcing the neutrino mass to be zero has been found in the period after 1957.

[22] A large number of such experiments are in progress at present (see, e.g., the content of the Proceedings quoted in ref. [48]).

[23] The experiments with solar neutrinos, for instance, can be sensitive to differences of squares of neutrino masses as small as 10^{-11} eV^2.

[24] All these questions continue to be actual today.

[25] It was extended to the general case of n active neutrinos by B. Pontecorvo in [52].

assumed to arise due to neutrino mass terms which were considered to be flavour-nondiagonal. Starting from 1977 and especially from 1979 on it was realized (see, e.g., refs. [36,54,38]) that such neutrino mass terms arise naturally in the gauge theories of electroweak interaction. Thus, approximately 22 years after it has been suggested, the possibility of the existence of neutrino mixing and of neutrino oscillations began and continues to be commonly considered as a very natural one. There will be very little surprise in the elementary particle physics community if, say tomorrow, it will be established that neutrinos possess nonzero masses and if neutrino oscillations will be definitely proved to exist, although the implications of such discoveries for elementary particle physics will be profound.

Very often B. Pontecorvo was much ahead of his time in his scientific ideas. As we have seen, this was the case, for example, with the suggestion that neutrinos can be detected in experiments performed at reactors, and especially, with the radiochemical Cl–Ar method of neutrino detection, with the idea of $\mu-e$ universality, and with the neutrino mixing and oscillation hypothesis.

The scientific life of B. Pontecorvo was remarkably coherent: from 1946 on neutrinos became his scientific passion and our present understanding of their experimentally established and their possible properties, of how they can be "seen" and used for physics research, is primarily based on his ideas and his results.

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