Bruno Pontecorvo: From slow neutrons to oscillating neutrinos

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Bruno Pontecorvo's work in neutrino physics is examined and due emphasis is given to the audacity of his ideas both theoretically and experimentally. The account ends with the first solar neutrinos detected by Raymond Davis in 1967 using the radiochemical method developed by Pontecorvo in 1945.
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I. INTRODUCTION

On 4 December 1930, Wolfgang Pauli sent a letter to a meeting of physicists in Tübingen where Hans Geiger and Lise Meitner, in particular, were present.[1] The letter stated in part:

> "As the bearer of these lines, to whom I ask you to listen graciously, will explain more exactly, considering the 'false' statistics of N-14 and Li-6 nuclei, as well as the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the energy theorem. Namely [there is] the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle, and additionally differ from light quanta in that they do not travel with the velocity of light: The mass of the neutron must be of the same order of magnitude as the electron mass and in any case not larger than 0.01 proton mass.—The continuous β-spectrum would then become understandable by the assumption that in β-decay, a neutron is emitted together with the electron in such a way that the sum of the energies of neutron and electron is constant . . . But I don't feel secure enough to publish anything about this idea, so I first turn confidently to you, dear radioactives, with the question as to the situation concerning experimental proof of such a neutron, if it has something like about 10 times the penetrating capacity of a γ-ray. I admit that my remedy may appear to have a small *a priori* [emphasis in original] probability because neutrons, if they exist, would probably have long ago been seen. However, only those who wager can win . . ."[2]

In this letter Pauli's "neutron" is what we now call the "neutrino." In a talk given in Pasadena in June 1931, Pauli reported his idea of a "very penetrating radiation of neutral particles, which has not been observed up to now," emitted in nuclear beta decay according to $(A,Z)\xrightarrow{\beta}(A,Z+1)+\text{electron}+\text{neutrino}$ (Ref. 1, p. 6). The available energy according to the conservation principle is distributed among the outgoing electron and neutrino and the recoil nucleus (a three-body reaction); thus, it gives rise to a continuous β spectrum.

At that time the commonly accepted nuclear model consisted of a system composed of A protons and (A–Z) electrons. The quantum mechanical difficulties stemming from the confinement of electrons within a volume of nuclear dimensions and the continuous beta-ray spectra were the two great stumbling blocks of nuclear theory at the end of the 1920s. A neutral particle of spin 1/2 obeying the exclusion principle and confined inside the nucleus also would explain the most dramatic difficulty encountered by the model. In 1928–1929, Franco Rasetti, Fermi's collaborator in Rome, showed that N^{14} obeys Bose–Einstein statistics, and not Fermi–Dirac statistics. From a study of the Raman effect of the rotational spectra of biatomic molecules with equal nuclei, Rasetti showed that N^{14} has spin $I=1$.[3] Various authors pointed out that an object consisting of n particles, all obeying Fermi–Dirac statistics, should obey Fermi–Dirac statistics for n odd and Bose–Einstein statistics for n even. According to the proton–electron model of the nucleus, N^{14} had to obey Fermi–Dirac statistics because it was assumed to consist of 21 particles obeying Fermi–Dirac statistics. This assumption and its comparison with the experimental results of Rasetti on nuclear structure prompted long discussions. The more popular view was that "when inside a nucleus, the electrons lose some of the properties that they have outside."[4]

Pauli was unsure of his idea, and thus he did not allow his lecture to be printed in the proceedings. During the Rome Congress on nuclear physics in October 1931, Pauli discussed his idea with Bohr and Fermi. The latter was very positive, while Bohr preferred to think that within nuclear distances, the conservation laws broke down.

It appears that the new particle hypothesized by Pauli was named the "neutrino" by Edoardo Amaldi, one of the young members of Fermi's group in via Panisperna, after Chadwick's discovery of the neutron at the beginning of 1932.[5]

At the seventh Solvay meeting on atomic nuclei in October 1933, Heisenberg reported on the structure of the nucleus, which, according to the theory advocated by Majorana, must consist of protons and neutrons only. Pauli recalled that "A general clarification took place . . . It was now evident that, on the basis of this conception of nuclear structure, the neutrinos . . . had to be fermions in order to conserve statistics in beta decay. Furthermore, Ellis reported on new experiments carried out by his student W. J. Henderson, which established the sharp upper limit of the beta spectrum (thus corresponding to a unique energy difference between parent and daughter nucleus) and consolidated its interpretation. In view of the new circumstances, my earlier precaution of delaying publication now seemed to me unnecessary." (Ref. 1, pp. 4–5).

Following Heisenberg's lecture at the Solvay meeting, Pauli officially communicated his ideas on the neutrino in the discussion, which were printed in the report of the conference.[6] Fermi was stimulated by the discussions at the Solvay conference and developed his theory of beta decay in which he applied quantum field theory to beta radioactivity at the end of 1933. According to Fermi, the emission of an electron and a neutrino is similar to the emission of light by an excited atom—neither the beta particle and neutrino nor the light quantum is contained in the atom before its emission. The emission of the beta particle is due not to electromagnetic interaction, but to a new class of interactions (much later it would be known as the weak interaction).

At the core of Fermi's theory is the idea that electrons and neutrinos can be created and destroyed, and that an electron and neutrino are created in the decay of a neutron to a proton.[7] This concept was very novel for its time. Pontecorvo recalled Fermi's idea: "When the excited Na atom emits the 5890 Å line, the photon is not sitting in the atom (it is created); similarly the electron and the neutrino are created when a neutron is changing into a proton."[8] The discovery of β^+ radioactivity, announced by Joliot on 15 January 1934 made clear that a nuclear proton can transform into a neutron and emit a positron and a neutrino, according to $p \xrightarrow{\beta+} n + e^+ + \nu$, analogous to $n \xrightarrow{\beta-} p + e^- + \overline{\nu}$. G. C. Wick immediately showed the consistency of the first process with Fermi's theory.[9] The Fermi–Wick theory already contains the distinction between β^- and β^+ neutrinos as conjugate particles. The adopted convention was opposite to that used today. We shall see that such a choice remained a matter of convention until the early 1950s.

But does the neutrino really exist? Fermi's theory contained a single free parameter, today called the Fermi constant, G_F, which determines the strength of the weak interaction and can be determined by measuring the decay rate of one of the allowed decays. G_F has the dimension of the inverse of a mass squared; to a good approximation $G_F \sim 1/(300\,M_P)^2$, where M_P is the mass of a proton. The large term in the denominator $(300\,M_P)$ is the reason why Fermi interactions are very weak in low energy phenomena, which include all of the radioactive decays.

Given two beta decay processes like

$$(A,Z) \to (A,Z+1) + e^- + \overline{\nu}, \tag{1a}$$

$$(A,Z) \to (A,Z-1) + e^+ + \nu, \tag{1b}$$

one expects to have inverse reactions such as

$$\nu + (A,Z) \to e^- + (A,Z+1), \tag{2a}$$

$$\overline{\nu} + (A,Z) \to e^+ + (A,Z-1). \tag{2b}$$

The probability of the inverse process described in Eqs. (2) is easily calculable by using the Fermi theory. Almost immediately after the Fermi paper in Zeitschrift für Physik,[7] Bethe and Peierls estimated the cross section for inverse β-decay to be $<10^{-44}\,\mathrm{cm}^2$.[10] If a beam of 10^{10} neutrinos were headed toward the Earth, approximately all but one would emerge on the other side. Such a tiny interaction would enable a neutrino in the range of a few MeV (the typical energy of the neutrinos emitted in beta decay) to penetrate more than 1000 light years of liquid hydrogen, a number most discouraging to one seeking to detect a neutrino. No wonder Bethe and Peierls concluded that, "there is no practically possible way of observing the neutrino."[11]

Neutrinos were considered to be such elusive particles that detecting them was considered to be impractical by most physicists, even if some stubborn ones continued to wonder about the feasibility of such experiments. Among these physicists was Chadwick, the discoverer of the neutron, who immediately felt obliged to search for the new neutral object.[12] One of the most determined, however, perhaps because of an unexpressed debt to Enrico Fermi, was Bruno Pontecorvo, who soon began to think about all sorts of problems concerning neutrinos.

In chasing the truth Pontecorvo continually kept at the frontiers of science, often being much ahead of his time in his scientific ideas, which were always related to fundamental phenomena. He had exceptional scientific intuition, which went hand in hand with his brilliant qualities as an experimental physicist; his experiments and projects of experiments were always masterpieces of experimental skill. For these reasons Bruno Pontecorvo is an extraordinary example for present and future generations of physicists.

II. FROM VIA PANISPERNA TO CHALK RIVER

> "After having graduated from the University of Rome I was appointed assistant in the Department of Physics. The subject of my studies was selected by Fermi and Segrè. It was a work in classical spectroscopy. In 1934 practically nobody at the Institute of Physics had anything to do with spectroscopy; everyone was feverishly busy investigating radioactivity induced by neutrons, and the seminars of the institute were dominated by 'nuclear' reports. All these circumstances resulted in my heart being much closer to the neutron studies carried out by Fermi and his colleagues than to my spectroscopic work, which I completed by the summer of 1934. Therefore I was very glad when, upon coming back to Rome from my holidays, I was asked to help in the neutron experiments."[13]

In the spring of 1934 Fermi had discovered neutron-induced artificial radioactivity. The next step was to try to activate all the elements, and to study all the radioactive isotopes formed. This formidable task was beyond the capabilities of a single person, even of Fermi. For this reason he asked Edoardo Amaldi, Emilio Segrè, Franco Rasetti, and the chemist Oscar D'Agostino to work with him. Some 60 elements were irradiated with neutrons over a short space of time, and new radioactive elements were discovered, and often identified, in at least 40 of them. The results obtained by the "Via Panisperna boys" demonstrated all the advantages of teamwork in science, which Fermi introduced for the first time in Rome. The great importance of these results was immediately clear, even if the outcome of this new line of research pioneered by Fermi and his group could not have been foreseen at the time.

In September Fermi assigned Amaldi and Pontecorvo the task of establishing a quantitative scale for the radioactivity induced in the bombarded elements. However, they immediately encountered difficulties because it became apparent that the activation depended on the conditions of irradiation. As Pontecorvo noticed accidentally, silver irradiated on wooden tables gained more activity than when it was irradiated on the usual marble table in the same room. Moreover, Amaldi and Pontecorvo were sure that some influence came from a little shed made of lead bricks for protecting from the radiation, which they called "castelletto" (little castle), and inside which the cylinder to be irradiated and the source were placed.

Bruno Pontecorvo (left), Antonio Rostagni, and Enrico Fermi (Ivrea, Italy, 1949).

To try to clear up the mysterious influence on the behavior of neutrons by the surrounding objects, and particularly the ''lead mistery'' which Amaldi and Pontecorvo jokingly termed the ''castelletto effect,'' Fermi decided to study the effect of placing a piece of lead before the incident neutrons. With no conscious prior reasoning, he instead took a piece of paraffin. The paraffin-filtrated neutrons coming from the Rn–Be source had the miraculous effect of powerfully activating the irradiated substances, being far more effective than those that fell directly on the target. Fermi immediately understood that the neutrons crossing a material rich in hydrogen would be slowed down by multiple elastic scattering with the hydrogen nuclei. Slow neutrons, which spend a longer time close to a nucleus, are much more effective in inducing nuclear transformations—and therefore radioactivity—in irradiated substances, than fast neutrons which impinge directly on the target from the source. This idea was contrary to the well-established experience with charged particles, whose capacity to promote nuclear reactions increased rapidly with their energy. That same evening of 22 October, at Amaldi's home, the group prepared a short letter to ''La Ricerca Scientifica,'' and Pontecorvo became a co-author of the famous article, ''Influence of hydrogenous substances on the radioactivity produced by neutrons I'' by Fermi, Amaldi, Pontecorvo, Rasetti, and Segrè, which was to become the starting point of a new series of letters to the same journal.[14]

Pontecorvo participated in all the activities of the Via Panisperna group until 1936, when he moved to the Institute of Radium in Paris and worked with Frédéric Joliot-Curie, who Pontecorvo considered to be his second master after Enrico Fermi. In Paris, he studied nuclear isomerism and predicted the existence of β-stable isomers, and also discovered the first of such isomers.[15]

The racial laws promulgated in Italy in the second half of 1938 affected Pontecorvo. Jews were expelled from all public schools, universities, and academies, and from all government jobs. After the occupation of France by German troops, Pontecorvo fled by bicycle from Paris to Toulouse, reached Lisbon by train, and embarked for the United States. With Segrè's help he found a job at Well Surveys in Tulsa, OK, where he worked from 1940 to 1942 proposing and implementing a method for oil prospecting using neutron logging.[16] The simple but ingenious device that Pontecorvo designed for this use clearly shows his distinctive experimental skill and scientific creativity. His method, still widely applied in practice, consisted in measuring the radioactivity induced by neutrons in rock, through which a borehole has been drilled. The well-logging instrument consisted of a strong neutron source and an ionization chamber well shielded from the rays coming directly from the source. As a consequence of the interaction of the primary rays from the source with the surrounding rock, the signals furnished by the ionization chamber varied with the properties of the strata. The radioactivity depends strongly on the presence in the rock of hydrogenous substances. The measurement of the radioactivity permits the determination of the presence of water and of oil in the rock.

Early in 1943, Pontecorvo, who had received interesting job offers in the oil industry, preferred to join the recently established Anglo-Canadian nuclear research laboratory in Montreal, whose staff included several distinguished scientists who were refugees from various European countries. At first he stayed in Montreal and worked on the NRX project, a proposed heavy-water natural uranium reactor. A site for the reactor was chosen a few kilometers north of Chalk River, about 150 km northwest of Ottawa. In December 1945 Pontecorvo moved there with his family, and lived at Deep River, a new settlement 15 km away.[17]

During 1943–1945, Pontecorvo, who was responsible for several physics aspects of the reactor, devoted almost all of his effort to design problems, and wrote 25 reactor related reports. During 1945–1946 he worked on a BF_3 neutron counter and on the development of sensitive neutron monitors for the start-up of the reactor. The chain reaction started early in the morning of 22 July 1947: only four physicists, including Pontecorvo, were allowed in the Control Room at the start up.

III. SPECULATING ON NEUTRINOS

In the meantime, Pontecorvo was thinking about using a nuclear reactor as a source of neutrinos. He wrote ''In 1946 neutrinos were generally considered undetectable particles. Many respectable physicists thought that the question about detecting free neutrinos was nonsense (not only because of temporary difficulties), just as nonsense as the question of whether the pression in a vessel is or is not, say, less than 10^{-50} atm.

Pontecorvo also commented that ''True, Pauli at the beginning did not recognize fully such inescapable implications of his idea,''[8] and recalled that Bethe and Peierls had used a general dimensional argument to show that neutrinos of energy ~1 MeV must have an astronomically large mean free path. Their argument yielded an estimate of the magnitude of the cross section of the inverse β process by which a free neutrino of comparable energy interacts with matter and is stopped. The cross section can be found by using only the empirical knowledge of β-decay lifetimes. Bethe and Peierls considered the beta decay process, which is allowed when the mass difference m between the initial and final nucleus is sufficiently large:

$$(A,Z)\rightarrow(A,Z+1)+e^{-}+\overline{\nu}, \tag{3a}$$

which takes place in a characteristic time τ. A possible inverse beta decay reaction is

$$\overline{\nu}+(A,Z+1)\rightarrow(A,Z)+e^{+}. \tag{3b}$$

If $1/\tau$ is the probability per unit time of a β disintegration involving an energy mc^2 for the emitted neutrino, the cross section σ_{inv} for the inverse beta process produced by a neutrino of that energy must be given by a formula of the type $\sigma_{\text{inv}}=K/\tau$, where K is a constant with the dimensions of area×time. The largest possible length involved in the inverse beta process is the wavelength λ corresponding to energies of the order of mc^2 of the impinging neutrino, and the longest time involved is this length divided by c. The process is thus characterized by an upper limit of the cross section

$$\sigma_{\text{inv}}\leqslant\lambda^2\frac{\lambda}{c}\,\frac{1}{\tau}. \tag{4}$$

Pontecorvo observed that Eq. (4) predicts that the cross section for the inverse β process produced by neutrinos will increase with the energy E of the impinging particle, provided that $1/\tau$ depends on a power of E larger than E^3 to compensate for the λ^3 factor. It was known at the time (mostly after Fermi's theory of the decay) that $1/\tau$ should increase at least as $\approx E^5$ for energies of the order of 1 MeV, which are characteristic of β-decay neutrinos. It was expected that the dependence would be considerably higher for very high energies. Pontecorvo concluded that the cross section for an inverse β process produced by neutrinos with the emission of a β particle could increase with a high power of the energy of the bombarding neutrino. In his own words: ''The argument, which today is self-evident (almost all good arguments look obvious 'a posteriori') made a deep impression upon me. I did not forget it many years later . . .''[8]

When the appearance of powerful nuclear reactors ''made free neutrino detection a perfectly decent occupation,''[8] Pontecorvo well remembered the Bethe–Peierls argument: ''The NRX Canadian reactor, in the design of which I was taking part, was not working yet, but it was clear to me that under the very compact shield, where the cosmic ray soft component was considerably weakened, one might dispose of a neutrino flux $\sim 10^{12}\,\text{cm}^{-2}\,\text{s}^{-1}$.''[8] With its 20 MW power and its neutron flux five times greater than any other reactor in existence $(6\times10^{13}\,n/\text{cm}^2\,\text{s})$, the NRX was the world's best research reactor at the time.

On 21 May 1945 Pontecorvo was the first to propose a method to detect free neutrinos in his P.D.-141 Chalk River report.[18] This proposal was followed by a lecture given on 4 September 1946 at a Nuclear Physics Conference in Montreal.[19]

IV. THE INVERSE β PROCESS

On 13 November 1946 a paper on the inverse β process appeared as a report of the National Research Council of Canada.[20] Pontecorvo began by remarking that ''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'' (Ref. 20, p. 21). After recalling the experimental facts that led Pauli to propose the neutrino hypothesis, Pontecorvo examined how the problem of β disintegration had been attacked by different types of experiments: beta-spectroscopy, that is, the study of the form of the spectrum, the relation between the energy release and the probability of disintegration, the ratio of positron to electron emission in cases where both electrons and positrons can be emitted, the ratio of the number of K capture transitions to positron transitions), neutron decay,[21] and the recoil of nuclei.[22] Because of its great penetrating power, the evidence for neutrino existence was only indirectly obtained on the basis of the laws of energy and momentum conservation.

About 70 years ago there was only one known process involving the neutrino, the beta decay of heavy nuclei, which has a three-particle final state. Pauli concluded his report on the Solvay conference of 1933 by saying that, ''. . . the experimental study of the momentum balance in β-decays is a problem of utmost importance; one can predict that the difficulties will be very great because of the smallness of the recoil energy of the nucleus.''[23] Bethe and Peierls, who examined various methods for deciding experimentally whether neutrinos exist, indicated that a way of deciding the question would be to observe the recoil of the nucleus in β-decay. Pauli suggested experiments of this type, and Leipunski performed the first of these in Cambridge. Although the results of the experiment were only qualitative, they suggested that conservation of momentum, in addition to conservation of energy and spin, could be maintained only if a third particle participated in the process.[24]

However, as Pontecorvo emphasized, ''The common feature of all these experiments was that the magnitude of the recoil energy of the nucleus having undergone a decay process is examined in the light of the laws of the conservation of energy and momentum . . . It should be noted that experiments of this type, while of fundamental significance in the understanding of the β process, cannot bring decisive *direct* (emphasis in original) evidence on the basic assumption of the existence of the neutrino'' (Ref. 20, p. 22). Pontecorvo's statement can be understood by keeping in mind that recoil experiments were interpreted on the assumption that energy and momentum are conserved in individual β processes. In effect, Pauli introduced the neutrino based on the validity of conservation laws in subatomic processes like the β-decay, which was the very starting assumption of his reasoning. Fermi's successful β-ray theory, which was built upon the neutrino hypothesis, clarified once and for all that the neutron is not a coupled proton–electron system: in the disintegration process, every transition from neutron to proton must be accompanied by the creation of an electron and a neutrino. An important result of Fermi's work was the determination of the energetic distribution of the emitted electrons. Fermi showed that the study of the high-energy end of this distribution could be used to establish an upper limit to the mass of the neutrino, and that available data favored a very small neutrino mass.

Physicists who attempted to observe the momentum of the recoiling nuclei undergoing β-decay simply said that energy and momentum are apparently not conserved. These experiments were of the *missing mass* type as proposed by Bethe and Peierls.[25] A logical difficulty was thus implied by such a circular chain of reasoning: the neutrino, as introduced by Pauli, had the role of carrying away the missing energy, momentum, and spin in the beta disintegration, making it possible to retain the conservation laws *at the location of the β-decay process*. To demonstrate the neutrino's existence, it was necessary to detect an interaction of the neutrino at a location remote from the point of origin.

In his paper, Pontecorvo quoted the latest most important results, in particular those obtained by J. S. Allen, who had studied the recoil of a nucleus having undergone a *K*-electron capture,[26] and by Jacobsen and Kofoed-Hansen,[27] who performed an experiment that took advantage of the fact that in the fission of uranium a noble gas isotope, Kr^{38}, is produced which undergoes two successive β-disintegrations. The interpretation of their results, obtained by measuring only the recoil momentum of the nucleus, was that the result was "incompatible with the assumption that there is no neutrino," even if it was not possible to go so far as to say anything about the angular distribution of the emission of the neutrino.[28] Crane and Halpern[29] came to analogous conclusions in 1938 by measuring the recoil of the nucleus using a cloud chamber and observing the electron and the nuclear recoil simultaneously; the momentum was not conserved in the system consisting of only the electron and nucleus. The errors were too big to permit them to say anything about the distribution of the angle between the electron and the neutrino, but the experiments suggested that the neutrino was needed to conserve momentum.

The measurement of the recoil of atoms formed in a *K*-electron capture process was also the one experiment that could distinguish sharply between the emission of single and multiple neutrinos. Because *K*-capture decay is not complicated by the emission of electrons, the very existence of a nuclear recoil would contradict the conservation of momentum unless the neutrino participates in the process. The possibility that the missing energy could be carried away by several particles, all at once or within a finite length of time, could not be completely overlooked. In *K*-capture the spectrum of recoils would be a line spectrum because the energy of the transformation is not shared between an electron and a neutrino, but is taken by the neutrino alone. Thus, the assumption that part of the energy of the decaying nucleus is carried away by a single neutrino can be examined experimentally by studying the nuclear recoil spectrum of an electron capture isotope. If the single neutrino picture is correct, the momentum of the recoiling nucleus would be equal to the momentum of the emitted neutrino, with the result that all nuclei should recoil with the same momentum. Allen had tested the possibility of single or multiple neutrino emission in 1942, but definitive conclusions could not be reached. In 1949, C. W. Sherwin experimented with P^{32} and concluded that the missing energy is carried away by a single neutrino.[30] In 1952, Rodeback and Allen verified the validity of momentum conservation in the emission of neutrinos with an experimental apparatus that used the *K*-capture reaction in ^{37}A. They stated, "the missing energy of a disintegration is shared between the recoil nucleus and a single neutrino. Linear momentum is shown to be conserved between the recoil nucleus and a single neutrino."[31] In 1952, R. Davis also measured the nuclear recoil spectrum of the electron capture isotope Be^7 and reached the same conclusion.[32]

In recalling the results of Allen and Jacobsen and Kofoed-Hansen,[26,27] Pontecorvo clearly stated that the recoil experiments added nothing that was really new; only direct observation of the interaction of the neutrino at a location other than its point of origin could be regarded as satisfactory demonstration of its existence, and hence of the validity of the fundamental energy conservation laws in nuclear β-decays. Pontecorvo wrote that the "Direct proof of the neutrino must, consequently, be based on experiments, the interpretation of which does not require the law of conservation of energy, that is, on experiments in which some characteristic process produced by *free neutrinos* (a process produced by neutrinos after they have been emitted in a β disintegration) is observed (emphasis in original)" (Ref. 20, p. 22). The importance of this statement cannot be overestimated: neutrinos can be shown to exist if they are detected after having traveled a certain distance.[33] Two years later, in 1948, Pontecorvo again stressed this concept by saying, "It was suggested by many physicists that experiments on the recoil of the nuclei in β-decay might confirm in a decisive way the existence of neutrinos . . . however, experiments of this type can only either *disprove* the neutrino hypothesis or *increase* the 'indirect' evidence for the existence of the neutrino (and at the same time give important information on the β-decay): a 'direct' proof of the neutrino existence, *different in character* from the evidence already available, cannot be obtained by recoil experiments."[34]

As Crane wrote in the same year the general attitude was that "Not everyone would be willing to say that he believes in the existence of the neutrino, but it is safe to say there is hardly one of us who is not served by the neutrino hypothesis as an aid in thinking about the β-decay process . . . While the hypothesis has had great usefulness, it should be kept in the back of one's mind that it has not cleared up the basic mystery, and that such will continue to be the case until the neutrino is somehow caught at a distance from the emitting nucleus."[28]

Fermi's theory was so attractive in its explanation of beta decay that the belief in the neutrino as a real entity was widespread. A 1952 article on "Does the neutrino really exist?" went so far as to state that the question of the existence was meaningless.[35] Nevertheless, many fundamental questions about these particles were being considered, particularly since 1936, when Gamow and Teller modified the Fermi Hamiltonian (where only vector currents are present) to include more general operators involving scalar, vector, axial vector, pseudoscalar, and tensor currents.[36] A long effort was required before the deepest nature of the Fermi interaction could be thoroughly investigated, both from an experimental and a theoretical point of view. In this context Pontecorvo would tackle some problems with brilliant ideas.

In May 1945, when Pontecorvo began to think about the possibility of detecting neutrinos, only three years had passed since the first nuclear pile had functioned in 1942, thanks to Fermi. The first explosion of a nuclear bomb, which was believed to produce a relatively short intense pulse of neutrinos, would occur on 16 July 1945. But at that time even Frederick Reines dedicated just ''a passing thought regarding neutrinos;'' his attention was directed mainly to the unusual phenomena that characterized the explosion, such as thermal radiation, gamma rays, and neutrons. The use of the large neutrino flux from a chain-reacting pile to test for the inverse β-decay process had been a subject of conversation among physicists since the advent of the pile.[33] The flux of neutrinos just outside a working pile was far greater than that from any terrestrial source then available. The γ-ray and neutron intensity is very close to zero due to the heavy shielding around the pile, but only in 1951 did Reines begin to think in real terms about the problem of detecting neutrinos. During the summer he met Fermi in Los Alamos and told him about his ''nascent idea,'' hoping that Fermi ''might have some useful comment.'' The conversation went as follows: ''I have been thinking about detecting neutrinos, and I think the bomb is the best source. Fermi thought for a minute and said yes that appeared to be so. Then I said it seemed to me that a detector with sensitive mass of one ton or so would be required. He agreed. I then said that I had no idea how to construct such a detector. He allowed that he did not either and that ended the conversation.'' A few months later Reines met Clyde L. Cowan, and they agreed that ''the detection of the neutrino was a supreme challenge.'' They gave a talk to the Physics Division at Los Alamos in which they described their ideas about a large liquid scintillator that had been constructed for use in the vicinity of a nuclear explosion, and mentioned the delayed coincidence between the product positron and neutron capture pulses to identify the neutrino interaction. During the discussion ''Kellog asked whether it might not be possible to use a fission reactor instead of a bomb.''[37] At first Reines and Cowan argued that it would not—both Fermi and Bethe had agreed that a bomb was the most promising source for such an experiment—but that same night during a telephone call they agreed that the delayed coincidence could be used to reduce the background from other events. Detecting the flashes from both the positron and the neutron as separate but related signals would make the reactor an attractive source.[37] There also were other advantages of using a reactor, such as the ease of repeating a measurement and the opportunity of extending the observation time to reduce statistical uncertainty.

Reines and Cowan dropped the idea of the bomb and decided to detect the large neutrino flux from the fission products of the Savannah River nuclear reactor.[37] The reaction $\overline{\nu}_e + p \rightarrow n + e^+$ can be produced on the protons of a water target containing cadmium chloride: the emitted positrons then annihilate with an electron giving two simultaneous photons; the final neutron is slowed down by the water and captured by the cadmium with a subsequent emission of delayed photons, 15 μs after the photon pair of the annihilation. On average they detected only 3 neutrino events/h and needed to run their experiment for 2085 h. After convincing themselves by means of a long series of tests that they were observing the neutrino, Cowan and Reines decided on 14 June 1956 to send Pauli a telegram: ''We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons.'' Later they learned that Pauli had consumed a whole case of champagne celebrating with some friends. One of the reasons for their success was the newly discovered scintillation of organic liquids, which they successfully used on the large (1 m^3) scale appropriate to their needs of detecting free reactor antineutrinos.[38]

In 1945/1946, about ten years earlier, when Pontecorvo was working in nuclear physics, scintillators had not yet been invented. All the evidence up to that time and even later was obtained ''at the scene of the crime.''[39] Direct proof of the existence of the neutrino must be based on experiments, the interpretation of which does not require the law of conservation of energy, that is, on experiments in which some characteristic process produced by neutrinos after they have been emitted in a disintegration is observed. ''It is clear that inverse β transformations produced by neutrinos are processes of this type'' claimed Pontecorvo, ''and certainly can be produced by neutrinos, if neutrinos exist at all.'' The observation of an inverse process produced by neutrinos was considered impossible at the time due to its extremely low yield, but Pontecorvo pointed out that ''this statement seems to be too drastic . . . the experimental observation of an inverse β process produced by neutrinos is not out of the question with modern experimental facilities'' (Ref. 20, p. 22).

Pontecorvo gave a general definition of inverse β processes as the transformation of a neutron into a proton produced artificially by bombardment with neutrinos, electrons, or γ rays. In connection with the reactions indicated in Eqs. (2), Pontecorvo remarked that the ''*actual emission* of a β particle . . . is certainly not detectable in practice. However, the nucleus of charge $Z \pm 1$, which is produced . . . may be (and generally will be) radioactive, with a well-known half-life (see, for example, Seaborg's Table of Radioelements). *Consequently the radioactivity of the produced nucleus may be looked for as proof of the inverse β process*'' (Ref. 20, p. 23) (emphasis in original).

The essential point of Pontecorvo's radiochemical method is that 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 time. Moreover, the radioactive atoms produced by inverse β-decay processes have different chemical properties from the irradiated atoms. Consequently, it might be possible to extract the radioactive atoms of known half-life produced by interactions of neutrinos from a very large mass of matter irradiated by neutrinos.

Pontecorvo had selected the elements to be considered for irradiation ''according to a compromise between their desirable properties'' (Ref. 20, p. 23). These were (1) the material to be irradiated must not be too expensive, because Pontecorvo had calculated that for neutrino irradiation the volume was limited only by practical considerations and might be as high as one cubic meter. (2) The nucleus produced in the inverse β transformation must be radioactive with a half-life of at least one day because of the long time involved in the separation. (3) The separation of the radioactive atoms from the irradiated material must be relatively simple. (4)

Because strong sources of high-energy neutrinos were not available, an important requirement was that the difference in mass of the element Z and $Z\pm1$ must be small. (5) The background, that is, the production of element $Z\pm1$ by other causes than the inverse β process, must be as small as possible.

A careful inspection of the Seaborg table of artificial radioisotopes indicated a few possible target candidates, by far the best of which was a chlorine compound, for which the reaction is

$$\nu+{}^{37}\mathrm{Cl}\rightarrow{}^{37}\mathrm{Ar}+e^{-}. \tag{5}$$

The ^{37}Ar decays by K-capture, transforming back to ^{37}Cl with the liberation of 2.8 keV of energy in the form of x rays and Auger electrons, which have a very short range which enable them to be more easily separated from background events in a Geiger counter. The experiment would consist in irradiating a large quantity of matter containing ^{37}Cl with neutrinos for the order of one month (the argon half-life is approximately 34 days), and extracting the radioactive ^{37}Ar. Argon is a rare gas and hence is chemically inert, which facilitates its separation from the chlorine. The radioactive argon would be put inside a counter, whose ‘‘counting efficiency is close to 100%’’ remarked Pontecorvo ‘‘because of the high Auger electron yield’’ (Ref. 20, p. 24). Nuclear reactors are a source of antineutrinos, according to the present-day convention for the particle associated to β^{-} decay, while the Cl–Ar reaction is triggered by neutrinos. For this reason Pontecorvo later remarked that ‘‘I wrote here ‘neutrino’ and not $\overline{\nu_e}$, because at the time the question as to whether $\nu\neq\overline{\nu}$ was not clear.’’[8] Because both the neutrino and antineutrino were thought to have the same zero mass, spin one-half, and zero charge, it was difficult to see how they differed physically. Indeed, for most purposes, the formal difference was ignored and both were frequently referred to as ‘‘neutrinos.’’ Moreover, in 1945/1946 only the electron neutrino was known, and nobody even suspected that there could be different species of neutrinos. The real nature of the ‘‘mesotron,’’ the particle that we now call the muon, was discovered only in 1947 in the famous experiment of Conversi, Pancini, and Piccioni.[40] The difference between electron neutrinos and antineutrinos produced in beta decay, and muon neutrinos and antineutrinos produced in pion and muon decays was resolved only later.

How was it that Pontecorvo had such a strong interest in neutrino initiated reactions? Apparently he was thinking of an inconclusive attempt suggested in 1936 by Joliot, who suspected that the light charged particles in β-decay could not be identical to electrons. He proposed to Pontecorvo a joint experiment to verify that that β-radioactivity could be induced by bombarding nuclei by β-rays, and not by electrons. However, the experiment with Joliot gave a negative result, and they did not publish anything. Nevertheless, Pontecorvo clearly stated, ‘‘in the following it always remained in my mind. This is why, in 1947, by association of ideas, I imagined the reaction: neutrino+chlorine 37→argon 37+electron.’’[41]

Pontecorvo told how he had discovered by chance one of the good practical reasons for this choice. Pontecorvo, Hanna, and Kirkwood started tests for a neutrino detector with ^{37}Ar prepared at the Chalk River reactor using the (n,γ) reaction: $n+{}^{36}\mathrm{Ar}\rightarrow{}^{37}\mathrm{Ar}+\gamma$. In those days scintillation counters did not exist, and proportional counters were used to detect strongly ionizing particles such as low energy protons and alphas, so that it was then believed that proportional counters should not work at gas multiplication factors larger than $\sim$100, which obviously is not true as far as an input ionization of a few ion pairs is considered. Probably because of this erroneous idea, the potentiality of proportional counters had not been recognized earlier, while the outstanding advantage of such devices is their ability to measure very low energy radiations, which in a nonmultiplying ionization chamber would be masked by the amplifier noise. ‘‘Well, once, looking at an oscilloscope connected to the counter, we saw plenty of pulses from ^{37}Ar equal in amplitude at voltages on the counter much lower than the Geiger threshold,’’ recalled Pontecorvo.[8] They discovered,[42] independently of Curran and co-workers in Glasgow,[43] the high gain regime (up to 10^6), of the Geiger–Müller counters, a special regime of operation of the proportional counters. They realized that large-gas-amplification proportional counters could be advantageous for detecting the 2.8 keV Auger electrons with low background, and in fact the pulses of such a counter are remarkably uniform in size. In recognizing the necessity of measuring the pulse amplitudes to help in distinguishing the background from genuine decay events, Pontecorvo was well aware of the fact that the success of the use of the Cl–Ar method (or of any other radiochemical method) for neutrino detection would depend on the level of suppression of the various background processes that could be achieved in a real experiment.[8]

In discussing the cross sections for the inverse β process, Pontecorvo (Ref. 20, pp. 24–25) used the dimensional argument given by Bethe and Peierls[10] and calculated that the effect might be detected with a neutrino flux of the order of 10^{14} neutrinos per cm^2/s. He commented, ‘‘Such a value of the neutrino flux, though extremely high, is not too far from what could be obtained with present-day facilities’’ (Ref. 20, p. 25).

In the last section of his paper on inverse β-decay (Ref. 20, p. 25), Pontecorvo mentioned that the neutrino flux from the Sun is of the order of 10^{10} neutrinos/cm^2 s. According to the Bethe cycle for the production of energy in the Sun,[44] about 6% of the energy is in the form of neutrinos. However, Pontecorvo dismissed solar neutrinos as not sufficiently energetic, but at the same time he put forward the idea of using railway car tanks filled with CCl_4 in a tunnel in the Canadian Rockies.[45] As an alternative he indicated two strong neutrino sources: ‘‘the pile itself, *during operation*’’—adding that ‘‘The advantage of such an arrangement is the possibility of using high energy neutrinos emitted by all the very short period fission fragments. Probably this is the most convenient neutrino source . . .’’ (Ref. 20, p. 25, emphasis in original) and the ‘‘hot’’ uranium metal extracted from a pile. Pontecorvo also considered the investigation of inverse β processes produced by electrons or γ rays of high energy, for which ‘‘the best source is a betatron or a synchrotron.’’

V. ON MAJORANA’S TRACKS

While passing through Zurich between 1947 and 1948, Pontecorvo had lunch with Pauli: ‘‘I told Pauli about my plans with the ^{37}Cl–^{37}Ar method; he liked very much the general idea and remarked that it was not clear whether ‘reactor neutrinos’ should definitely be effective in producing the reaction ($\nu+{}^{37}\mathrm{Cl}\rightarrow{}^{37}\mathrm{Ar}+e^{-}$), but he thought that they probably would.’’ Pontecorvo commented on Pauli’s argument by saying: "... as you see, this is the Majorana point of view."[8] In his last paper published in 1937,[46] Majorana introduced a "truly neutral neutrino," a fermion that cannot be distinguished from its antiparticle. Pontecorvo remarked, "Majorana, putting the question about an electrically neutral fermion being described either by his theory or by the Dirac theory, implicitly introduced the notion of charges other than electrical."[8] In 1937, when Majorana invented truly neutral fermions, only the notion of electric charge was known. "Dirac particles," as implicitly foreseen by Majorana, should have a "non-electric" charge, a "signature" related to the particle–antiparticle conjugation property. This signature was afterwards referred to as the "leptonic charge" or "leptonic number." The advantage of this method over the elementary interpretation of Dirac equations, claimed Majorana, is that there was no longer any reason to assume the existence of antineutrons or antineutrinos.[46]

The different inverse β-decay behavior of Dirac and Majorana neutrinos was discussed for the first time by Racah almost immediately after the appearance of Majorana's paper: "If some day the experiments would demonstrate that such a distinction between ν_e and $\overline{\nu_e}$ does not exist in nature, that is, that any neutrino can indifferently produce emission of electrons and positrons, it would become necessary ... to apply to the neutrinos the formalism of Majorana."[47]

A Royal Society discussion held in March 1937 conveys the then attitude, when precursor Majorana was already speculating about the real nature of antiparticles: "There can be no two opinions about the practical utility of the neutrino hypothesis ... until clear experimental evidence for the existence of the neutrino can be obtained ... the neutrino must remain purely hypothetical ... The detailed theory ascribes to [the neutrino] ... a free path in matter so great that failure to detect any evidence of interaction between neutrino and matter is no evidence against its existence."[48] Pontecorvo had well in mind Majorana's paper: "I personally was faced with the Majorana neutrino-Dirac neutrino dilemma more than once and each time for long periods. The first time when I proposed and developed the Cl–Ar method of detecting neutrinos ..."[8] He had thought about the possibility of detecting such elusive particles probably since the times of his inconclusive experiment with Joliot,[41] but he must have considered Majorana's theory as a concrete reality from the beginning, being very familiar with neutrinos since the time of his work with Fermi's team at via Panisperna. It is clear that Pontecorvo was deeply affected by Majorana's phrase, "Although it is perhaps not possible now to ask to experiment to choose between the new [Majorana's theory] and that in which the Dirac equations are simply extended to neutral particles, one should keep in mind that the new theory is introducing in this unexplored field a smaller number of hypothetical entities ..."[8]

As Pontecorvo mentioned, the question as to whether $\nu \neq \overline{\nu}$ was generally not clear at the time. When Cowan and Reines began to work for their experiment, they too considered the two processes of inverse β decay as involving a "unique" neutrino, with the emission of an electron or a positron: $\nu+(A,Z)\leftrightarrow(A,Z-1)+e^{+}$ or $\nu+(A,Z)\leftrightarrow(A,Z+1)+e^{-}$. According to Reines "It was not known in 1952 whether the neutrinos emitted in e^{+} or e^{-} decay were identical (Majorana) or differed (Dirac). We chose to focus on the reaction $\nu+p\rightarrow n+e^{+}$, because of its simplicity and the possibility that the scintillation of organic liquids ... might be employed on the large scale ... appropriate to our needs."[33]

At a time when weak interactions were involved only with nuclear β-decay, the distinction between the neutrino and antineutrino in the absorption and emission of such particles could not but generate the formulation of a question that Pontecorvo attributed to Majorana: "From one phrase of Majorana I quoted above it is seen that he definitely had in mind the question as to whether the Majorana versus Dirac nature of a fermion could be established by modern (1937!) experiments ... Majorana probably thought about experiments which in principle might answer the following question: are neutral leptons emitted, say, together with negative beta rays, capable of being absorbed by nuclei with the emission, again, of negative electrons? I think that probably he did not mention explicitly such a possibility because at the time detecting neutrinos was unfortunately and wrongly considered neither a serious proposal nor even a decent argument of conversation (the expected cross section being ridiculously small!)."[8] Thus, it appears that Pontecorvo's deep interest in the nature of neutrinos was the core motivation of his proposal, as can be inferred from the cogent logic of his reasoning and from his detailed discussion about the conceptual meaning of the experiment he had imagined.

Probably during 1948, Pontecorvo discussed the ^{37}Cl–^{37}Ar method with Fermi in Chicago. Later Pontecorvo and Fermi met at the Basel–Como conference of 1949 on the occasion of Fermi's return in Italy nearly ten years after his departure. "Fermi was not at all enthusiast (*sic*) about neutrino applications of the method," recalled Pontecorvo, "but liked very much our proportional counters, with the help of which together with Hanna we first observed L-capture (in ^{37}Ar, ~250 eV, ~10 ion pairs) and measured the ^{3}H spectrum going quite down at the time with the upper limit of the neutrino mass."[8] The technique was used to study the β spectrum of tritium, which was found compatible with a neutrino mass $\leqslant$500 eV, a significant result in those days.[49]

Bruno Pontecorvo moved to England in 1949, and the idea of detecting neutrinos was abandoned at Chalk River. He loved traveling, and it also appears that he preferred to live in Europe, near his parents and brothers. His defection to USSR in 1950 is still remembered as an important episode of the Cold War in Britain. Historians have claimed that Pontecorvo was an atomic spy who since World War II had passed secret nuclear information to the Soviets. On the contrary, it appears that he defected because he was very scared by the witch-hunts occurring in the U.S. and Great Britain. He had joined the underground Italian communist party in 1936, because he hated the fascist regime, and the war in Spain threatened to spread it. He had communist relatives in Italy, and although he regarded himself as uninterested in politics, the intensification of arrests on both sides of the Atlantic, often only on the base of political ideas, may have been the motivation for his choice, which he connected to his personal feelings about the atmosphere of those times: "I considered terribly unfair and amoral the deep feeling of hostility nourished after the war by the Western countries towards USSR, who had given a decisive contribution on gaining the victory over the Nazi, at the cost of untold sufferings."[50] Thanks to new public and private documents only recently released, new light was shed on his career and the episode of his defection.[51] He stayed in Bristol until 1950, when he moved to the USSR and started to work at the

Institute of Nuclear Problems of the Academy of Sciences in Dubna, near Moscow. "Until 1950 I continued to think about the problem and to test low background proportional counters in that connection and in connection with solar problems. For example I remember that Camerini, who at the time was working in Bristol and was a great specialist in cosmic ray stars, helped me to calculate the cosmic ray background in various Cl–Ar experiments which I was planning to do . . . Since 1950 I stopped experimenting on the problem because I happened to work in an accelerator laboratory (not in a reactor laboratory) and also as there was no site deep underground enough in the USSR for a solar experiment . . . However, I kept thinking about counters (. . . and the Sun)."[8]

Luis Alvarez reconsidered the use of this method of detecting the neutrino in an unpublished 1949 work.[52] He proposed an experiment capable of detecting the theoretically expected cross section for neutrinos of $2\times10^{45}\,\mathrm{cm}^2$. Alvarez also stressed that "the most important experimental problems lie in the elimination of the various types of background," a problem that continued to be equally important in subsequent experiments with neutrinos. In proposing the use of chlorine as a detector for reactor neutrinos, Alvarez, like Pontecorvo, explicitly assumed that neutrinos and antineutrinos were equivalent. Pontecorvo's paper,[20] a report from the Chalk River Laboratory in Canada, was classified by the U. S. Atomic Energy Commission until 1949, most probably because the word "pile" appears several times in discussion of the possible existing intensive sources of neutrinos, and it was feared that the method could be someway used to measure the power output of reactors or bombs. In this connection it is worth recalling that Fermi's pile, the first nuclear reactor, began functioning in December 1942, and the first nuclear explosion occurred in the summer of 1945 under the secrecy of Manhattan Project. During the same time Pontecorvo was using the reactor for his experiments.

VI. DAVIS TAKES UP THE CHALLENGE

In the meantime Raymond Davis, a young radiochemist at Brookhaven National Laboratory, was searching for something interesting on which to work.[53] He had found Crane's stimulating review of 1948 which contained an extensive discussion on recoil experiments[28] and one of the earliest discussions of the Sun as a source of neutrinos: "I was hooked on neutrinos from the beginning," recalled Davis in his Nobel Lecture.[53] He took up the quest of detecting solar neutrinos, and spent the first year working on inconclusive experiments on the recoil of ^{107}Ag from the electron-capture decay of ^{107}Cd. His next step was a successful study of the recoil energy of a ^{7}Li nucleus resulting from the electron-capture decay of ^{7}Be.[54] In the introduction Davis reported the results of the latest analogous experiments and discussed the problem concerning "the question of single or multiple neutrino emission" during the process. At the end of the article he wrote, "one can conclude that ^{7}Be electron capture decays are accompanied by the emission of a single neutrino."[54]

In 1951, Davis began working on a radiochemical experiment for detecting neutrinos from a fission reactor: "Bruno Pontecorvo's short paper was quite detailed, and the method he described, removing argon by boiling carbon tetrachloride and counting ^{37}Ar in a gas-filled counter, has many similarities to techniques I eventually used . . . It was not clear at that time, however, whether neutrinos and antineutrinos were different particles, nor was it clear how they could differ. After all, there are other examples in nature where the particle is its own antiparticle, such as the photon and the pi-zero."[53]

On 21 September 1954 the Physical Review accepted Davis' paper, "Attempt to detect the antineutrinos from a nuclear reactor by the $^{37}Cl(\overline{\nu},e^-)^{37}Ar$ reaction."[55] After recalling that in this reaction, "a neutrino (ν) is emitted which may be formally distinguished from an antineutrino ($\overline{\nu}$) which accompanies negative beta emission," Davis stated: "A nuclear reactor emits antineutrinos . . . In our experiment an attempt is made to observe an inverse electron capture process which requires neutrinos, using a source emitting antineutrinos. If neutrinos and antineutrinos are identical in their interactions with nucleons, one should be able to observe the process upon carrying the experiment to the required sensitivity. However, if neutrinos and antineutrinos differ in their interactions with nucleons, one would not expect to induce the reaction $^{37}Cl(\overline{\nu},e^-)^{37}Ar$. A positive experiment of this type could show that these particles are not to be distinguished in their nuclear reactions. A negative experiment carried to the required sensitivity would indicate that neutrinos and antineutrinos differ in their nuclear reactions, or that the present theory of beta decay is incorrect."[55]

In the Davis experiment a large 3900 l (1000 gallon) tank of carbon tetrachloride (C_2Cl_4) liquid was irradiated over a long period of time by antineutrinos from the Brookhaven reactor. The container was placed outside of the iron shield surrounding the reactor's graphite cube. At this location a high flux of 3 to 4×10^{11} antineutrinos per cm^2 per s was anticipated. After every run atoms of ^{37}Ar were extracted from the liquid by purging it with ^{4}He gas and were detected by a low-background Geiger counter. The γ-quanta produced in the capture by ^{37}Ar were detected. No effect was observed, and an upper limit on the cross section of $2\times10^{42}\,\mathrm{cm}^2$ was placed for fission product antineutrinos. Davis observed that the experiment "was not sensitive enough to detect the theoretically computed cross section and therefore conclusions could not be drawn concerning the correctness of beta decay theory, or the identity of neutrinos and antineutrinos," and ended by saying that "the present experiment will be continued in an effort to accomplish this purpose."[55]

Because the 1000 gallon tank with its associated counters were more sensitive for detecting neutrinos than any previously reported device, Davis considered also the possibility of detecting neutrinos from the Sun at the surface of the Earth. Measurements with the container shielded from cosmic rays by 19 ft of Earth permitted placing a crude upper limit on the neutrino flux from the Sun related to the proton–proton chain and the carbon–nitrogen cycle processes, which was about 40 000 SNU, a factor of 15 000 above his eventual result of 2.56 SNU. (The solar neutrino unit, or SNU, is defined as 10^{-36} captures per target atom per second.) "One reviewer of my paper," recalled Davis in his Nobel Lecture, "was not very impressed with this upper limit and commented: Any experiment such as this, which does not have the requisite sensitivity, really has no bearing on the question of the existence of neutrinos. To illustrate my point, one would not write a scientific paper describing an experiment in which an experimenter stood on a mountain and reached for the moon, and concluded that the moon was more than eight feet from the top of the mountain."[53]

It was also clear that the Brookhaven reactor was not a powerful enough neutrino source, so in 1954 Davis built an experiment using 3800 l of CCl_4 in one of the basements of the Savannah River reactors, at the time the most intense antineutrino source in the world. The sensitivity for detecting neutrinos and the flux at Savannah River were sufficiently high to provide a critical test for the neutrino–antineutrino identity. In 1956, during a meeting of the American Physical Society, Davis reported a preliminary result that the cross section for the reaction was less than $0.9\times 10^{-45}\,\mathrm{cm}^2/\mathrm{atom}$. He pointed out that if the neutrino and the antineutrino had been identical, the theoretical value $\sigma \approx 2.6\times 10^{-45}\,\mathrm{cm}^2$ would have been expected (based on measurements of the gross beta spectrum for U^{235} fission products).[56] In 1957 the cross section for this process was found to be $<0.25\times 10^{-45}\,\mathrm{cm}^2$, a factor of 10 below the cross section calculated assuming neutrino–antineutrino identity.[57] The reaction $\overline{\nu}+{}^{37}\mathrm{Cl}\rightarrow e^- + {}^{37}\mathrm{Ar}$ was not observed: ''The result is consistent with the principle of lepton conservation'' concluded Davis. This experiment could be also used to set an upper limit on the solar neutrino flux.[58]

While Davis was at Savannah River, Reines and Cowan and their associates were performing their experiment on the first detection of a free antineutrino. This experiment was a clear demonstration that the neutrino postulated by Pauli was indeed a real particle, and Davis' experiment showed that these antineutrinos did not drive the reaction: according to these results the neutrino was not its own antiparticle. This meant that leptons (the term was first used by Abraham Pais and Christian Møller in 1947 to indicate both electrons and neutrinos) are characterized by a specific ''charge'' relating electrons and neutrinos (+1) and positrons and antineutrinos (−1). If lepton number is conserved, the reaction $\overline{\nu}+{}^{37}\mathrm{Cl}\rightarrow e^- + {}^{37}\mathrm{Ar}$, which is associated with the process $\overline{\nu}+n\rightarrow p+e^-$, is forbidden, while the success of Cowan and Reines' experiment with $\overline{\nu}+p\rightarrow n+e^+$ showed that this latter process is allowed. In fact, according to present-day theories, the underlying neutrino physics is more complex. Today we know that if neutrinos have a small but nonzero mass, the process proposed by Pontecorvo (a β^- decay followed by the $\overline{\nu}$ capture by ^{37}Cl) is absolutely forbidden if the neutrino is a Dirac particle (that is, if ν and $\overline{\nu}$ are different objects), and is possible if the neutrino is a Majorana particle ($\nu \equiv \overline{\nu}$) and its mass is nonvanishing. In this case the rate of the process is very strongly suppressed, and unobservable in practice. It is still a fundamental and unresolved question whether the neutrino is a ''Dirac'' or ''Majorana'' particle.

Now Davis took on the next challenge: detecting neutrinos from the Sun. The Sun's energy comes from the fusion of four protons to make a helium nucleus, but only some of these reactions produce neutrinos detectable by the chlorine–argon experiment. Astrophysicists generally believed in the 1950s that the Sun operated predominantly on the $p-p$ chain and that the only significant production of neutrinos was from the proton–proton reaction that initiates this chain: $p+p\rightarrow {}^2\mathrm{H}+\nu_e+e^+$. In this reaction, a proton decays to a neutron in the vicinity of another proton forming a heavy hydrogen nucleus called deuterium and emitting a positron and a neutrino. These neutrinos have a maximum energy of only 0.4 MeV. Because the chlorine detector has a threshold of 0.86 MeV, it is incapable of detecting these $p-p$ neutrinos. The only neutrinos expected to come from the Sun with sufficient energy to be absorbed by chlorine were those from ^{13}N and ^{15}O in the CNO cycle. At a time when an experiment to detect solar neutrinos did not seem feasible, the situation changed dramatically when it became clear that the rate of the reaction ${}^3\mathrm{He}+{}^4\mathrm{He}\rightarrow {}^7\mathrm{Be}+\gamma$ is 1000 times greater than had been previously thought. One in 10 000 ^{7}Be nuclei captures a proton to make ^{8}B. The flux of energetic neutrinos from the decay of ^{8}B to ^{8}Be is low, because the ${}^7\mathrm{Be}(p,\gamma){}^8\mathrm{B}$ reaction plays only a minor role in the solar energy generation process. However, the cross section is so large that the ^{8}B neutrinos would be expected to produce about 90% of the total signal in the detector based on the ${}^{37}\mathrm{Cl}(\nu,e^-){}^{37}\mathrm{Ar}$ reaction. A large chlorine experiment was proposed[59] that was inspired by detailed calculations by John Bahcall in 1963.[60] ''Only neutrinos,'' claimed the author, ''with their extremely small interaction cross sections, can enable us *to see into the interior of a star* and thus verify directly the hypothesis of nuclear energy generation in stars'' (emphasis in original).[60] The theory provided guidance on how large a tank to build: the predicted production rate was 4 to 11 ^{37}Ar atoms per day in 378 000 l of perchloroethylene. This experiment became operational in 1967, and Davis was the first to detect solar neutrinos produced in the solar reactions that power the Sun.[61] It is interesting to note that the production of B^8 in the Sun depends strongly on the central temperature. Therefore a measurement of the B^8 neutrino flux allows us to deduce an accurate value for the central temperature of the Sun. Also the main flux of solar neutrinos originating from the fusion of two protons into deuterium accompanied by the emission of a positron and neutrino, whose energy Pontecorvo had initially judged to be too small, could later be detected on the basis of transitions induced by these neutrinos in the nuclei of gallium and germanium ($\nu_e+{}^{71}\mathrm{Ga}\rightarrow \mathrm{e}^-+{}^{71}\mathrm{Ge}$), the threshold of which is only 0.23 MeV. The experiments, SAGE (Soviet American Gallium Experiment) and GALLEX (involving scientists from Germany, France, Italy, Israel and US), were done in two underground laboratories with such large amounts of gallium, and were completely unthinkable in 1946.

As Pontecorvo in retrospect remarked about Fermi's lack of enthusiasm in 1949 regarding neutrino applications of Pontecorvo's methods: ''I understand very well Fermi's reaction. As I think that Segrè said, Don Quixote was not a hero of Fermi. He could not have sympathy for an experiment which, true, grace to the heroic efforts of R. Davis, terminated very brilliantly, but many, many years after its conception.''[8]

VII. THE END OF THE STORY?

After about 20 years Pontecorvo's radiochemical method had revealed all its power, leading to the creation of an important new field of research, neutrino astronomy. But the last word on solar neutrinos had not been told. To everyone's surprise, even after the first run of Davis' experiment, the chlorine detector captured many fewer neutrinos than Bahcall had predicted. The results were challenged and checked repeatedly over the following three decades by other experiments, but always with the same result: the Sun produces one-third as many neutrinos as expected. Were the theories wrong, or did we know less than we thought about the Sun?

The solar neutrino puzzle was to have a rather unexpected solution. Already in 1957, in analogy to K–antiK oscillations, Pontecorvo introduced the purely quantum-mechanical concept of neutrino–antineutrino oscillations, although he was not aware of the existence of multiple neutrino flavors: ''. . . if the conservation law of neutrino charge would not apply, then in principle neutrino-antineutrino transitions could take place in vacuum.''[62] At that time Davis was doing his experiment with reactor antineutrinos, and Pontecorvo decided to study in detail the possibility that ''neutrino and antineutrino are mixed particles, that is, symmetric and antisymmetric combination of two truly neutral Majorana particles ν_1 and ν_2 having different combined parity.''[63] In 1957 Pontecorvo also suggested that this possibility could be tested experimentally: ''So, for example, a beam of neutral leptons consisting mainly of antineutrinos when emitted from a nuclear reactor, will consist at some distance *R* from the reactor of half antineutrinos and half neutrinos.'' However, he remarked that such effects ''may be unobservable in the laboratory because of the large values of *R*, but will certainly occur, at least, on an astronomic scale.''[64] In 1967 he anticipated the solar neutrino problem. In mentioning Davis' proposed experiment, he pointed out that, due to neutrino oscillation, the ''flux of observable Sun neutrinos must be two times smaller than the total . . . neutrino flux.''[65] At the end of the section ''Possibility of oscillations $\nu \Leftrightarrow \bar{\nu}$, $\nu_\mu \Leftrightarrow \nu_e$ in vacuum'' Pontecorvo remarked: ''Although what is written above is at best extremely rough and at worst entirely wrong, I will continue to speculate on oscillations in neutrino beams.''[66] In 1969, just one year after the problem was recognized, Pontecorvo and Gribov proposed the basic idea underlying the correct solution of the solar neutrino problem: lower energy solar neutrinos switch from electron neutrino to another type as they travel in the vacuum from the Sun to the Earth. The process can go back and forth between different types, and the number of oscillations depends upon the neutrino energy.[67]

It required many years of effort to reveal the effects of very small neutrino masses and neutrino mixing. More than three decades were needed in order to show that new particle physics was required to explain what happened to the neutrinos on their way to detectors on Earth from the interior of the Sun. In the meantime the attention of many physicists was increasingly attracted to the problem of neutrino mass and neutrino oscillations.

Pontecorvo's bold ideas have been definitely verified during the past few years, when clear evidence for the phenomenon of flavor oscillations that many physicists had long regarded as an ''intellectual luxury,'' has been obtained. In 1998 the SuperKamiokande experiment showed evidence for the oscillations of atmospheric neutrinos; shortly afterward, in 2002, the SNO experiments obtained conclusive evidence for the oscillations of solar neutrinos, confirming the earlier results of Raymond Davis and Masatoshi Koshiba. They both obtained the Nobel prize in Physics 2002 ''for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos.''[68] These results also solved the mystery of the missing solar neutrinos. The SNO experiment was capable of measuring both the flux of electron neutrinos coming from the Sun, and the total neutrino flux (summing over all three neutrino flavors). These measurements revealed the existence of a large flux of muon and/or tau neutrinos from the Sun. Since all neutrinos generated deep inside the Sun are all created with the electron flavor, the results clearly demonstrated that neutrinos can change flavor during their propagation. The ''missing solar neutrinos'' of previous experiments (that were only sensitive to the electron flavor) were not really missing, but only present with a different flavor. In 2003, ''terrestrial'' evidence (with human-made neutrino sources) for flavor oscillations was obtained using reactor neutrinos (KamLAND) and accelerator neutrinos (K2K).[69]

In the second half of the twentieth century neutrino physics underwent major developments, which saw Pontecorvo as a leading worker in the effort to understand the mysteries of the weak interaction. Describing how neutrinos were his passion during his entire scientific life would require a long and fascinating historical reconstruction. However, this initial story about the challenge of detecting neutrinos, illustrates the extraordinary character of this great physicist, and his strong intuition about the physics of neutrinos, the most elusive particles in the universe.

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[2]For an English translation of the whole letter, see L. Brown, ''The idea of the neutrino,'' Phys. Today **31**(9), 23–28 (1978).

[3]F. Rasetti, ''On the Raman effect in diatomic molecules,'' Proc. Natl. Acad. Sci. U.S.A. **15**, 234–237 (1929); **15**, 515–519 (1929).

[4]Quoted in J. Chadwick, ''The existence of a neutron,'' Proc. R. Soc. London, Ser. A **136**, 692–708 (1932). For a detailed discussion about the difficulties of the electron–proton model of the nucleus, see R. H. Stuewer, ''The nuclear electron hypothesis,'' in *Otto Hahn and the Rise of Nuclear Physics*, edited by W. R. Shea (Reidel, Dordrecht, 1983), pp. 19–67.

[5]The ''neutrino,'' a funny and grammatically incorrect contraction of ''little neutron'' (in Italian neutronino), entered the international vocabulary through Fermi, who used it sometime between the conference in Paris in July 1932 and the Solvay Conference in October 1933, where Pauli used it. The word arose in a humorous conversation at the Istituto di via Panisperna. Fermi, Amaldi, and a few others were present and Fermi was explaining Pauli's hypothesis about his ''light neutron.'' To distinguish this particle from the Chadwick neutron, Amaldi jokingly used this funny name. Quoted by Ugo Amaldi in the preface to *20th Century Physics: Essays and Recollections. A Selection of Historical Writings by Edoardo Amaldi*, edited by G. Battimelli and G. Paoloni (World Scientific, Singapore, 1998).

[6]W. Pauli, ''Structure et Propriétès des Noyaux Atomiques,'' *Rapp. Septième Conseil Phys. Solvay, Brussels 1933* (Gauthier-Villars, Paris, 1934), p. 324. An English translation of the comments can be found in Ref. 2, p. 27.

[7]His first article appeared in December 1933 with the title ''Tentativo di una teoria dell'emissione dei raggi β'' (Tentative theory of beta rays), E. Fermi, *La Ricerca Scientifica* **4**(2), 491–495 (1933), but Fermi intended to announce the results of his theory in a letter to Nature. The submission was rejected with a note explaining that it was ''too remote from physical reality to be of interest to the readers.'' (F. Rasetti, introductory note to Fermi paper Nos. 76, 80*a*, 80*b*, 80*c*, in E. Fermi, *Note e Memorie* (Academia Nazionale dei Lincei, University of Chicago Press, Roma, 1962), Vol. I, p. 540). He then sent a longer paper, ''Tentativo di una teoria dei raggi β,'' to Nuovo Cimento and its German translation to Zeitschrift für Physik (''Versuch einer Theorie der β-Strahlen. I.''); E. Fermi, Nuovo Cimento **11**, 1–19 (1934) and Z. Phys. **88**, 161–171 (1934).

[8]B. Pontecorvo, ''The infancy and youth of neutrino physics: some recollections,'' in *Colloque International sur l'Histoire de la Physique des Par-*

ticules, Journal de Physique, Suppl. (Paris) **43**(2), 221–236 (1982).
[9]G. C. Wick, ''Sugli elementi radioattivi di F. Joliot e I. Curie,'' Rend. Acad. Naz. Lincei **19**, 319–324 (1934).
[10]H. Bethe and R. Peierls, ''The 'Neutrino,''' Nature (London) **133**, 532–533 (1934); **133**, 689–690 (1934).
[11]In 1935 Nahmias was able to place an upper limit at one primary encounter of neutrinos with matter in 3×10^6 km of path in air. See M. E. Nahmias, ''An attempt to detect the neutrino,'' Proc. Cambridge Philos. Soc. **31**, 99–107 (1935).
[12]J. Chadwick and D. E. Lea, ''Attempt to detect a neutral particle of small mass,'' Proc. Cambridge Philos. Soc. **30**, 59–61 (1934). In his Bakerian lecture of 1920 Rutherford already had speculated about a neutral (composite) particle, which later he named the neutron. He and his co-workers had searched for it during a twelve-year period, and it is well known that Chadwick's actual discovery took only ''a few days of strenuous work.'' See A. Pais, *Inward Bound* (Oxford U.P., Oxford, 1986), quote on p. 397.
[13]B. Pontecorvo, ''The discovery of slow neutrons: Some recollections,'' lecture delivered at the Jubilee session of the IV International School in Neutron Physics in Dubna, on 8 July, 1982, in *B. Pontecorvo, Selected Scientific Works. Recollection on B. Pontecorvo*, edited by S. M. Bilenky, T. D. Blokhintseva, I. G. Pokrovskaya, and M. G. Sapozhnikov (Società Italiana di Fisica, Editrice Compositori, Bologna, 1997), pp. 388–391, quote on p. 388.
[14]E. Fermi, E. Amaldi, B. Pontecorvo, F. Rasetti, and E. Segrè, Ric Sci. **5**(1), 283–284 (1934). The second article, with the same title, was by E. Fermi, B. Pontecorvo, and F. Rasetti, ''Influence of hydrogenous substances on the radioactivity produced by neutrons. II,'' *ibid.* **5**(1), 330–331 (1934).
[15]B. Pontecorvo, ''Nuclear isomerism and internal conversion,'' Phys. Rev. **54**(7), 542 (1938).
[16]B. Pontecorvo, ''Neutron well logging. A new geological method based on nuclear physics,'' Oil Gas J. **40**, 32–33 (1941). Between 1941 and 1943 Pontecorvo filed four patent applications for geophysical prospecting instrumentation.
[17]For thorough discussions of Pontecorvo's scientific work and personal recollections, see S. M. Bilenky, ''B. M. Pontecorvo and the neutrino,'' in *B. Pontecorvo, Selected Scientific Works*, Ref. 13, pp. XIII–XVIII; G. Fidecaro, ''Bruno Pontecorvo: From Rome to Dubna,'' Ref. 13, pp. 472–486; S. T. Petcov, ''On B. Pontecorvo contributions to weak interaction and neutrino physics,'' in Proceedings of the Sixth International Workshop on Neutrino Telescopes, Istituto Veneto di Scienze, Lettere ed Arti, Venice, 22–24 February, 1994, edited by M. Baldo Ceolin, pp. 17–26.
[18]B. Pontecorvo, Report P.D.-141, Chalk River Laboratory, 21 May, 1945.
[19]See G. Fidecaro, ''Bruno Pontecorvo: From Rome to Dubna,'' Ref. 17, p. 478.
[20]B. Pontecorvo, ''Inverse β process,'' in *B. Pontecorvo, Selected Scientific Works*, Ref. 13, pp. 21–29. It was published as Report P.D.-205 of the National Research Council of Canada Division of Atomic Energy, Chalk River, Ontario, 20 November 1946. It was declassified and issued by the Atomic Energy Commission in 1949.
[21]By that time the transformation of a free neutron into a proton had not yet been detected, although plans for its detection, as well as for the study of the angular distribution of the proton and electron emitted, had been made in several laboratories, including Chalk River, where Pontecorvo was working.
[22]O. Hahn and L. Meitner, ''Eine neue Methode zur herstellung radioaktiver Zerfallsprodukts,'' Verh. Dtsch. Phys. Ges. **11**, 55–61 (1909). They introduced the recoil method of radioactive analysis and found that a negatively charged plate placed near a plate coated with radioactive elements became radioactive by collecting the recoil atoms whose recoil energy could be analyzed by a retarding field.
[23]W. Pauli, *Rapp. Septième Conseil Phys. Solvay, Brussels 1933* (Gauthier-Villars, Paris, 1934), p. 324.
[24]A. I. Leipunski, ''Determination of the energy distribution of recoil atoms during β-decay: Existence of neutrino,'' Proc. Cambridge Philos. Soc. **32**, 301–303 (1936).
[25]The experiments initiated in 1936 by Leipunski, Ref. 24, with the residual-nuclei distribution following the β^+-decay of $^{11}_{6}C$, continued with the more satisfactory 1938 experiments by Crane and Halpern. See H. R. Crane and J. Halpern, ''New experimental evidence for the existence of a neutrino,'' Phys. Rev. **53**, 789–794 (1938), who measured the recoil of $^{38}_{18}$Ar in $^{38}_{17}$Cl β^--decay.
[26]J. S. Allen, ''Experimental evidence for the existence of a neutrino,'' Phys. Rev. **61**, 692–697 (1942). The electron capture transition $p+e^-\rightarrow n$ +neutrino, mostly involves *K*-electrons, which have a high probability of being captured inside the nucleus due to their small binding energy, even in heavy nuclei. This process is another inverse β reaction that was suggested in 1934, first by G. C. Wick, Ref. 9, and independently by Bethe and Peierls, Ref. 10, pp. 689–690, and observed by Alvarez in 1938. See L. W. Alvarez, ''The capture of orbital electrons by nuclei,'' Phys. Rev. **54**, 486–497 (1938).
[27]J. C. Jacobsen and O. Kofoed-Hansen, ''Recoil of the nucleus in β-decay,'' Det. Kgl. Danske Vidensk. Selskab, Mat.-Fys. Med. **23**, paper No. 12 (1945).
[28]Their experiment is thoroughly discussed in H. R. Crane, ''The energy and momentum relations in the beta-decay, and the search for the neutrino,'' Rev. Mod. Phys. **20**, 278–295 (1948), quote on pp. 285–288.
[29]H. R. Crane and J. Halpern, Ref. 25, and ''Recoil of nucleus in β-decay,'' Phys. Rev. **56**, 232–237 (1939). Their experiment, as well as Allen's, was considered a ''More satisfying direct observation of the neutrino'' by Konopinsky in his review ''Beta-decay,'' Rev. Mod. Phys. **15**, 209–245 (1943).
[30]C. W. Sherwin, ''Neutrinos from P^{32},'' Phys. Rev. **75**, 1799–1810 (1949). Sherwin tested the single neutrino hypothesis, and examined the nuclear recoil spectrum from a β-emitting nucleus in order to define the direction and energy of the electron and the direction of the recoil.
[31]Their experimental setup used the *K*-capture reaction in ^{37}A. The recoil of the Auger electrons can be neglected, so the momentum of the neutrinos manifests itself only in the recoil of the Cl atoms. See G. W. Rodeback and J. S. Allen, ''Neutrino recoils following the capture of orbital electrons in A^{37},'' Phys. Rev. **86**, 446–450 (1952).
[32]R. Davis, Jr., ''Nuclear recoil following neutrino emission from Beryllium7,'' Phys. Rev. **86**, 976–985 (1952).
[33]Reines and Cowan later considered the possibility that the neutrino emitted from fission could not survive ''the 11 meter journey from the reactor'' to the detector. F. Reines, ''Neutrinos to 1960-Personal recollections,'' in *Colloque International sur l'Histoire de la Physique des Particules*, Ref. 8, pp. 237–255, quote on p. 252.
[34]B. Pontecorvo, ''The neutrino and the recoil of nuclei in beta disintegrations,'' Rep. Prog. Phys. **11**, 32–42 (1948) (emphasis in original).
[35]S. M. Dancoff, ''Does the neutrino really exist?,'' Bull. Atom. Sci. **8**, 139–141 (1952).
[36]G. Gamow and E. Teller, ''Selection rules for the β-disintegration,'' Phys. Rev. **49**, 895–899 (1936).
[37]F. Reines, ''The early days of experimental neutrino physics,'' Science **203**, 11–16 (1979), quote on p. 11.
[38]The technique of scintillation counting received great impetus from the development of the photo-multiplier tube and the crucial observation that liquids could be made to scintillate with high efficiency when the scintillating compound was at low concentration. See M. Ageno, M. Chiozzotto, and R. Querzoli, ''Sulla nuova tecnica dei contatori a scintillazione,'' Atti Accad. Naz. Lincei, Cl. Sci. Fis., Mat. Nat., Rend. **6**, 626–631 (1949); G. T. Reynolds, F. B. Harrison, and G. Salvini, ''Scintillation in liquid scintillation counters,'' Phys. Rev. **78**, 488 (1950); H. Kallmann, ''Scintillation counting with solutions,'' *ibid.* **78**, 621–622 (1950); M. Ageno, M. Chiozotto, and R. Querzoli, ''Scintillations in liquids and solutions,'' *ibid.* **79**, 720 (1950).
[39]F. Reines, ''The neutrino from poltergeist to particle,'' Nobel Lecture, 8 December 1995. Available at ⟨http://www.nobel.se/physics/laureates/1995/reines-lecture.pdf⟩.
[40]M. Conversi, E. Pancini, and O. Piccioni, ''On the disintegration of negative mesons,'' Phys. Rev. **71**, 209–210 (1947).
[41]M. Pinault interviewed Pontecorvo on 9 December 1991. For the page of the original document reproducing the quoted sentence of the interview with manuscript corrections by Pontecorvo, see J. Laberrigue-Frolow, ''Bruno Pontecorvo and Paris,'' in *B. Pontecorvo, Selected Scientific Works*, Ref. 13, pp. 461–471, quote on p. 469. Pontecorvo's date is incorrect; actually his very first proposal was in 1945.
[42]They developed a complete technique for precise measurements of energy: G. Hanna, D. Kirkwood, and B. Pontecorvo, ''Fluctuations of ionization and low energy beta-spectra,'' Phys. Rev. **74**, 497–498 (1948); ''High multiplication proportional counters for energy measurements,'' *ibid.* **75**, 985–986 (1949).
[43]D. C. Curran, J. Angus, and A. L. Cockcroft, ''Beta spectrum of Tritium,'' Nature (London) **162**, 302–303 (1948).
[44]H. A. Bethe, ''Energy production in stars,'' Phys. Rev. **55**, 434–456 (1939). In this paper, neutrinos were not included explicitly in the nuclear reactions.

[45]Quoted in G. Fidecaro, ''Bruno Pontecorvo: from Rome to Dubna,'' Ref. 17, p. 479.

[46]E. Majorana, ''Teoria simmetrica dell'elettrone e del positrone,'' Nuovo Cimento **5**, 171–184 (1937); English translation by L. Maiani, ''Symmetric theory of the electron and the positron,'' Soryushiron Kenkyu **63**, 149–162 (1981).

[47]G. Racah, ''Sulla simmetria tra particelle e antiparticelle,'' Nuovo Cimento **14**, 322–328 (1937).

[48]C. D. Ellis, ''A discussion on β-type of nuclear transmutations,'' Proc. R. Soc. London, Ser. A **161**, 447–450 (1937), p. 447.

[49]Counters with low effective background found their natural application in the measurement of low-energy β-spectra of gaseous materials, as for instance, tritium. B. Pontecorvo, G. C. Hanna, and D. Kirkwood, ''Nuclear capture of L electrons,'' Phys. Rev. **75**, 982 (1948); G. C. Hanna and B. Pontecorvo, ''The β-spectrum of ^{3}H,'' *ibid.* **75**, 983–984 (1949).

[50]B. Pontecorvo, ''Una nota autobiografica,'' in *B. Pontecorvo, Selected Scientific Works* Ref. 13, pp. 424–430. Only in 1978 Pontecorvo was allowed to travel abroad, to Italy, to take part in the celebrations in honor of Edoardo Amaldi on the occasion of his 70th birthday. In 1991/1992, when he was writing his biography he confided to his friend Gershtein: ''Nearly all my life I considered communism a science, but I now see it is not a science, but a religion. I thought Sakharov a very good, but naive person, and now I see it was I who was naive.'' Recollections about Pontecorvo's life in USSR can be found in S. S. Gershtein, ''Interesting recollections and reflections about Bruno Pontecorvo,'' in *B. Pontecorvo, Selected Scientific Works*, Ref. 13, pp. 440–454, quote on p. 445.

[51]S. Turchetti, ''Atomic secrets and governmental lies: Nuclear science, politics and security in the Pontecorvo case,'' Bri. J. History Sci. **36**(4), 389–415 (2003).

[52]L. Alvarez, Report UCRL-328, 18 April 1949, University of California, Berkeley.

[53]R. Davis, Jr., ''A half-century with solar neutrinos,'' Nobel Lecture, 8 December 2002. Available at ⟨http://www.nobel.se/physics/laureates/2002/davis-lecture.pdf⟩, quote on p. 59.

[54]R. Davis, Jr., ''Nuclear recoil following neutrino emission from beryllium 7,'' Phys. Rev. **86**, 976–985 (1952).

[55]R. Davis, Jr., ''Attempt to detect the antineutrinos from a nuclear reactor by the $Cl^{37}(\overline{\nu},e^-)A^{37}$ reaction,'' Phys. Rev. **97**, 766–769 (1955).

[56]R. Davis, Jr., ''An attempt to detect the antineutrinos from a nuclear reactor by the $Cl^{37}(\overline{\nu},e^-)A^{37}$ reaction,'' Bull. Am. Phys. Soc. **1**, 219 (1956).

[57]R. Davis, Jr., ''An attempt to observe the capture of reactor neutrinos in chlorine-37,'' in *Radioisotopes in Scientific Research, Proceedings of the First UNESCO International Conference, Paris 1957* (Pergamon, London, 1958), Vol. 1, p. 728.

[58]R. Davis, Jr. and Don S. Harmer, ''Attempt to observe the $Cl^{37}(\overline{\nu},e^-)A^{37}$ reaction induced by reactor antineutrinos,'' Bull. Am. Phys. Soc. **4**, 217 (1959).

[59]R. Davis, Jr., ''Solar neutrinos. II. Experimental,'' Phys. Rev. Lett. **13**, 303–305 (1964).

[60]J. N. Bahcall, ''Solar neutrinos. I. Theoretical,'' Phys. Rev. Lett. **12**, 300–302 (1964).

[61]R. Davis, Jr., D. S. Harmer, and K. C. Hoffman, ''A search for neutrinos from the Sun,'' Phys. Rev. Lett. **20**, 1205–1209 (1968).

[62]B. Pontecorvo, ''Mesonium and antimesonium,'' Ref. 13, pp. 144–147, quote on p. 146.

[63]B. Pontecorvo, ''Inverse β-processes and non-conservation of lepton charge,'' Ref. 13, pp. 152–154, quote on p. 153.

[64]Reference 63, p. 154.

[65]B. Pontecorvo, ''Neutrino experiments and the question of leptonic-charge conservation,'' Ref. 13, pp. 249–258, quote on p. 256.

[66]Reference 65, quote on p. 253. For a detailed discussion on these items see S. M. Bilenky and B. Pontecorvo, ''Lepton mixing and neutrino oscillations,'' Phys. Rep. **41**, 225–261 (1978); W. M. Alberico and A. M. Bilenky, ''Neutrino oscillations, masses and mixing,'' hep-ph/03066239. See also S. Bilenky, ''Neutrinos,'' *Encyclopedia of Physical Science and Technology*, 3rd ed. (Elsevier, Amsterdam, 2004), Vol. 10, p. 395.

[67]They derived explicit formulas describing oscillations $\nu_e - \nu_\mu$ assuming that ν_e and ν_μ are a superposition of two Majorana neutrinos. V. Gribov and B. Pontecorvo, ''Neutrino astronomy and lepton charge,'' Phys. Lett. B **28**(7), 493–496 (1969).

[68]See ⟨http://www.nobelprize.org/physics/laureates/2002/index.html⟩.

[69]Y. Fukuda *et al.* (Super-Kamiokande Collaboration), ''Evidence for oscillation of atmospheric neutrinos,'' Phys. Rev. Lett. **81**, 1562–1567 (1998); Q. R. Ahmad *et al.* (SNO Collaboration), ''Direct evidence for neutrino flavor transformation from neutral-current interactions in the Sudbury Neutrino Observatory,'' *ibid.* **89**, 011301-1–4 (2002); K. Eguchi *et al.* (KamLAND Collaboration), ''First results from KamLAND: evidence for reactor anti-neutrino disappearance,'' *ibid.* **90**, 021802 (2003); M. H. Ahn *et al.* (K2K Collaboration), ''Indications of neutrino oscillation in a 250-km long-baseline experiment,'' Phys. Rev. Lett. **90**, 041801-1–4 (2003).

JAMES CLERK MAXWELL

Those in the know honour Maxwell alongside Newton and Einstein, yet most of us have never heard of him. This is an injustice and a mystery but most of all it is our own great loss. His was a life for all of us to enjoy. He was not only a consummate scientist but a man of extraordinary personal charm and generous spirit: inspiring, entertaining and entirely without vanity. His friends loved and admired him in equal measure and felt better for knowing him.

Basil Mahon, *The Man Who Changed Everything: The Life of James Clerk Maxwell* (Wiley, 2003), p. 3.