

Bruno Pontecorvo and his inverse β process to detect neutrinos. A page of history

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Summary. — Bruno Pontecorvo's contributions to neutrino physics are well known. Bruno himself was very proud of his results, some time feeling a bit neglected. How did he land on neutrino physics? I found interesting to go back with the years and place Bruno in his time.

1. – The Pauli neutrino

In 1927 C.D. Ellis and W.A. Wooster [1] discovered, in a calorimeter experiment, that the total average energy deposited in the calorimeter, following the disintegration of Radium E was 344 ± 40 KeV, close to the average spectral energy of disintegration of the Radium E (350 KeV), but much smaller than the 1 MeV upper limit of the Radium E continuous spectrum.

Soon afterwards Lise Meitner and W. Orthmann [2] repeated the Ellis and Wooster experiment fully confirming (1930) their result. They found an average energy per β particle of 337 ± 20 KeV.

Assuming that the missing energy was taken away by a new invisible particle Pauli saved the energy conservation law questioned the same year (1930) by Niels Bohr. Customarily the history of the discovery of the neutrino begins with the famous letter *Dear radioactive Ladies and Gentlemen* addressed on December 4th 1930 by Wolfgang Pauli to Lise Meitner, for delivery to people discussing radioactivity in a meeting at Tübingen that he couldn't attend because of a ball (the Italian students ball) in Zürich.

To be more precise Pauli was addressing two different problems at the same time: “the ‘wrong’ statistics of the N- and the Li⁶-nuclei, and the mystery of the continuous β -spectrum as well, so to save together the alternation law of statistics and the energy law”. Electrically neutral particles, that Pauli called neutrons, having spin 1/2 and a mass of the order of the electron mass, in any case not larger than 0.01 times the proton mass, and satisfying the exclusion principle, could well exist in the nuclei.

The validity of the Wigner's theorem concerning the statistics of nuclei had been questioned in 1929 by W. Heitler and G. Herzberg after F. Rasetti pointed out that

although “N₂ and H₂ had a similar electronic structure they behaved in opposite ways as to the relative weight of odd and even rotational states”.

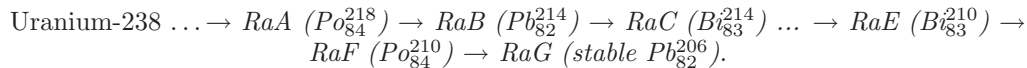
The solution was found soon. In 1929 the Nitrogen nucleus N₇¹⁴ was known as an ensemble of 14 protons and 7 electrons (inside the nucleus), namely 21 spin 1/2 particles, an odd number and FD statistics. In 1932 after the discovery of the neutron by Chadwick the composition changed: 7 protons and 7 neutrons, namely 14 spin 1/2 particles, an even number and BE statistics.

Nearly at the same time (1931), in the course of a scientific conference in Rome also attended by Pauli and Bohr, the new invisible Pauli’s neutral particle became known as “neutrino”.

2. – From H. Becquerel to C.D. Ellis, a flash

The experiments of Ellis and Wooster and of Lise Meitner and W. Orthmann are generally ignored though they are the conclusion of a long historical period that started in 1896 with the discovery of radioactivity by Henri Becquerel. The problems of radioactivity were not particularly under the specific attention of the physics community in a period so rich of other developments. Rather they *were principally the concern of a fairly modest-sized but elite club of experimental radioactivists. In those days, theoretical physicists did not play any role of consequence in the development of this subject . . .*, as written by Abraham Pais in his “Inward Bound of Matters and Forces in the Physical World”, [3] page 103.

As for β -emitters, only elements at the top of the Mendelejev scale were available for the experiments, or elements in their decay chains like, for example, the radium chain from Uranium-238:



Lower atomic number β -emitters became only available after the discovery of the neutron in 1932.

The properties of the emitted β -rays, recognized as being electrons in 1902 by W. Kaufmann [4], were initially investigated by measuring their absorption while traversing thin metal foils. The foil electroscope was generally used to measure β -ray currents. It was common belief that β -rays were absorbed according an exponential law [5] : $I(d) = I(0)e^{-vd}$. v is the velocity of the β -particles, dependent on the nature of the absorbing material (not on d), with v being in general different for different energies.

In the course of their systematic absorption measurements in the period 1907-1909, reported in several papers to *Physikalische Zeitschrift* Otto Hahn and Lise Meitner developed a method to separate radioactive atoms of the desired species, known as recoil method [6]. Radioactive daughters recoiling with force out of the thin surface where the mother species is deposited flew onto an opposite surface producing there a new source of incomparable purity.

The recoil method played an important role in the study of the radioactive chains from the large atomic number β -emitters. It is still used today for the extraction of large quantities of atoms of the desired species from isotopes produced by nuclear reactors.

A drastic change took place in 1909-1910 with the development of a magnetic spectrometer by William Wilson at the Manchester Rutherford laboratory. His magnetic spectrometer is known today as the multichannel spectrometer, where a beam of charged particles injected into a uniform magnetic field comes back after describing semicircles

of different diameter according to the momentum. Wilson was still using the foil electro-scope to measure the ionisation current.

Wilson proved that the absorption was not exponential. It was linear [7, 8].

Hahn and Meitner, after an argument with Wilson, designed their own experiment, at the Physics Institute with Otto von Baeyer (there were no magnets at the Chemistry Institute). They replaced the foil electro-scope with photographic plates.

The first sign of line spectra was reported by von Baeyer and Hahn in a first paper [9]. They also found that radioactive substances did not only emit α -rays, but also β -rays, with velocities characteristic of the species considered, thus confirming the ideas of Hahn and Meitner. However in a sequel [10] to that paper, together with Lise Meitner, though still interested to look for secondary causes possibly rendering inhomogeneous the beam initially homogeneous (as Lise Meitner confirmed several years later), they admitted that the β -spectrum of pure substances was “inhomogeneous”.

During the next few years the magnetic separation and photographic detection was adopted in several laboratories. Von Baeyer, Hahn and Meitner extended their earlier investigations [11, 12]. Important contributions came also from Jean Danysz in Paris [13]. Rutherford together with Robinson reported [14] 16 and 48 line spectra, respectively from Radium B and Radium C decay. No sign of a continuous spectrum was detected in the years 1910-1913 by photographic plates.

In 1913, James Chadwick was awarded a grant that could not be used to carry out research in Manchester, where he had studied under Rutherford. He decided to go to Berlin and work with Geiger at the Physikalisch Technische Reichsanstalt. In January 1914 he informed Rutherford that he and Geiger wanted to count the β -particles in the various spectrum lines from a mixture of Radium B (Pb_{82}^{214}) and Radium C (Bi_{83}^{214}).

Chadwick reported the detail of his work to the *Deutsche Physikalische Gesellschaft* in April 1914 [15]. He used an 180° magnetic spectrometer and, as electronic detector, a rudimentary device consisting in *a metal plate and a very clean needle with a sharp point*.

He found a continuous spectrum with four lines superimposed on the lower energy part of the spectrum, as found by others in previous experiments. He also made tests that convinced him that the continuous spectrum was not due to secondary scattering.

On July 28, 1914 the First World War started and Chadwick was interned in a war prisoner camp in Germany as an enemy alien, where he was authorized to set up a small physics laboratory. He was permitted to have some contact with Geiger. He could also exchange occasionally correspondence with Rutherford in England, and even receive some physics journals like *Nature*.

On June 4, 1915 Rutherford reviewed the knowledge status of radioactivity in a lecture at the Royal Institution [16]. He concluded that each atom does not emit an identical β radiation. The results were best explained by supposing that the β -ray spectrum is the statistical effect due to a large number of atoms decaying.

Three years after the end of the war a new character, Charles Drummond Ellis, already introduced in this paper [1], appeared on the stage. C.D. Ellis, a British artillery officer, was captured while on holiday in Germany after the start of the war. He found himself in the same camp where Chadwick had been interned, whom he met. While helping him in his laboratory he developed a great interest in physics, to the point to give up his career as artillery officer in 1919 and start physics at Cambridge where after the arrival of Rutherford he became his student. At Cavendish he developed in a short time into an highly experienced experimentalist.

His first paper in 1921, though not directly related to the Chadwick work in Berlin, raised in 1922 the interest of Lise Meitner [17] still stuck to her classic view of the primary β -ray energy redistributed by secondary effects, refusing any statistical interpretation.

In a few words, Meitner's 1922 paper started an argument with Ellis that was only settled in 1930, after Ellis measured with a calorimeter the total average energy emitted by the decay of Radium E, so to include all forms of known energy [1]. She then decided to repeat the Ellis experiment [2], a very difficult one indeed, to prove that the Ellis result was wrong. She, the fine experimentalist that she was, confirmed instead, with even higher precision, that the Ellis result was right.

3. – A Pontecorvo review

The work to search for the neutrino started in the first half of the thirties by the study of the dynamics of the β disintegration. The energy and the momentum of the recoiling nucleus and of the β particle could be measured. Provided the upper limit of the β spectrum was known, the mass of the neutrino μ_ν could be determined. A constant value of μ_ν should result from observations of a β particle and the associated recoil, independently of the energy of the β particle to prove the existence of the neutrino.

It should be noticed that while the experiments done in the twenties could only be based on the use of the existing natural radioactive elements, the experiments done in the thirties and the first half of the forties were only based on the use of radioactive elements produced artificially. Namely the much wider choice of radioactive materials potentially available allowed the experimentalist to better diversify the experiments taking advantage of the larger variety of methods and of the instrumentation becoming available.

The result of experiments by A.I. Leipunski, H.R. Crane and J. Halpern, J.S. Allen, J.C. Jacobsen and Kofoed-Hansen, listed in chronological order, were published in the period 1936-1945.

At the end of that period, in 1943-45 at Montréal, Pontecorvo was working as responsible of several physics aspects of the NRX reactor, essentially on reactor design problems. In 1945-46 at Chalk River, he worked on instrumentation more closely related to the start of the NRX reactor.

As recalled in my previous recollections [18] Pontecorvo moved from France to the United States of America in 1940, where he was engaged as research physicist by a US firm "Well Surveys, Inc." at Tulsa, Oklahoma. He was the first to develop the neutron well logging technique, still used today in oil fields. In 1943 he became a member of the British staff of the Montréal Laboratory, National Research Council of Canada. Studies were under way with a view to the design of a heavy water natural uranium reactor, a powerful research reactor later known as NRX reactor - for National Research X-perimental - that, built near Chalk River, was launched in July 1947.

It is conceivable that, with the launch of the reactor approaching and the work around it decreasing, Pontecorvo started considering new fields of work. His lasting interest in radioactivity after his work in the Fermi's group, the limitations intrinsic to recoil experiments and, last but probably not least, the proximity of a powerful research reactor - a neutrino factory in modern language - suggested him to look for new ways to see neutrinos.

In his first neutrino paper, a review paper, Pontecorvo discussed the 1936-1945 recoil experiments in considerable detail [19]. Because of the war Volume XI covered two years, the year 1946 and the year 1947. It was published in 1948. From the contents list, the

Pontecorvo's paper must have been accepted in 1946. Previous Pontecorvo's papers were classified and as such were only seen by authorized institutions.

Only the introductory part of the Pontecorvo's paper is briefly summarized here below.

The main difficulty of β recoil experiments comes from the small mass of the β particle, compared with the large mass of the α particle. For example, the recoiling Radium B nucleus, from α -decay of Radium A, acquires an energy of 110,000 eV (2% the energy of the α particle energy), while the recoiling Radium C nucleus, from β -decay of Radium B, acquires only an energy of 0.4 eV.

The 1909 Hahn and Meitner recoil method to separate radioactive atoms of the desired species and to prepare pure radioactive sources is then recalled [6]. As an example of use of such a method for radioactive analysis Pontecorvo recalls the work that led Hahn and Meitner to conclude in favour of a complex nature of Radium C [20].

As for the main experimental facts, the most precise measurement of M. Lecoïn and I. Zlotowski [21] done in 1939 at the Marie Curie's Institute du Radium is recalled in addition to the calorimetric measurements of Ellis and Wooster [1] and of Meitner and Orthmann [2]. At the Institute du Radium, by working with tenths of milli Kelvin temperature changes (compared to the milli Kelvin changes of the previous experiments) Lecoïn and Zlotowski found an average disintegration energy of $320,000 \text{ eV} \pm 5,000 \text{ eV}$.

Pontecorvo then refers to the Fermi's theory of the β decay, that being very successful in explaining the experimental facts strongly supported the neutrino hypothesis. If many physicists suggested that experiments on the recoil of nuclei in β decay might confirm in a decisive way the existence of neutrinos, for Pontecorvo experiments of that type could only either *disprove* the neutrino hypothesis or *increase* the "indirect" evidence of its existence. Pontecorvo wants a "direct" proof of the neutrino existence *different in character* from the evidence already available, that cannot be obtained by recoil experiments *unless the experiments are performed with sufficiently accurate accuracy*. Pontecorvo tries to mention specifically all the information which could be obtained by a sufficiently accurate experiment.

In the end, for Pontecorvo the only way of obtaining *direct* evidence for the neutrino's existence was by the detection of some specific process produced by *free neutrinos* i.e. a process produced by neutrinos after they have been emitted in a β disintegration. Inverse β transformations produced by neutrinos were processes of this type and certainly were produced by neutrinos, if neutrinos existed at all. "A method which might make it possible to observe β processes produced by neutrinos has been suggested by the author (1946)".

4. – The Pontecorvo inverse β process

The method suggested by Pontecorvo in his review paper [19], is known as $C\beta^{37}-A^{37}$ *Inverse β Process*. It was presented on 4 September 1946 by him at the Nuclear Physics Conference, Montréal, organized at McGill for graduated students by the National Research Council of Canada. The exact date of the conference was kindly communicated to me in the course of my visit to Chalk River at the end of May 1997 by Dr. Donald G. Hurst.

No Conference Proceedings were published, only a few lectures. The Pontecorvo lecture, issued as Report P.D.-205 and dated 20 Novembre 1946, [22] was immediately classified by the U.S. Atomic Energy Commission. It was declassified on October 8, 1949, nevertheless it remained unknown to the scientific community (except authorized Institutions like the Brookhaven National Laboratory and others).

Only in 1988, thanks to the efforts of W.F. Davidson, National Research Council of Canada, an afresh typed copy of the archived version of P.D.-205 in poor shape at NRC was made available. Dr. Malcolm Harvey, Director of the Physics Division of the Chalk River Laboratories sent me a copy of the original in good shape in June 1996.

Apparently nobody was aware that Pontecorvo had already been interested in inverse β decay experiments to see neutrinos. In his internal report P.D.-141 dated May 21, 1945 also classified, [23] *On a method for detecting free neutrinos*, he had considered as an example a Cl^{35} - S^{35} *Inverse β Process* experiment. I learned it from Geoffrey C. Hanna, a close Pontecorvo's collaborator, who on October 24, 1996 sent me a copy of P.D.-141, as I reported in my previous recollections [18].

Sometimes Alvarez is credited with having invented the Chlorine-Argon method "independently" from Pontecorvo. As remarked also by S.T. Petkov [24] in his article on Pontecorvo's contributions to weak interactions and neutrino physics, this credit does not appear justified. I even discussed the matter with Hanna at Chalk River in 1997 [18].

We only know the 1949 Alvarez's UCRL report [25]. There he substantially discussed cosmic-ray background extensively, after a quick recall of the inverse β process (that everybody knows was proposed by Bethe in 1936) and of its Chlorine-Argon application described in detail four years before by Pontecorvo in his two classified Chalk River reports. Very likely Alvarez had access to classified reports.

Alvarez is also credited for having proposed the use of Sodium Chloride (NaCl) for the Chlorine-Argon method. I only know that in 1939 H.R. Crane performed a toptable Chlorine-Sulfur inverse K_e capture experiment (totally forgotten today) using NaCl and a strong MsTh source [26-28], that I cannot discuss here.

5. – The two Chlorine isotopes

Natural Chlorine is a mixture of two stable isotopes, Cl^{35} and Cl^{37} , in the proportion of 75% and 25% respectively. As for the physics aspects the two applications of the proposed method cannot really be considered separately.

To be more precise, the inverse β process consists in the creation of radioisotopes by free neutrino interactions with stable nuclei, together with the emission of β particles. The radioisotopes then decay into β particles and neutrinos, thus returning the original stable isotopes (the direct process). The inverse process is bound to exist and the detection of radioisotopes is proof of neutrino existence.

However, according to the Fermi theory the neutrino cross-section is extremely small (less than 10^{-42} cm²). It had been currently stated that it was impossible to observe such processes. Purpose of Pontecorvo's efforts *was to show that the experimental observation of an inverse β process was "not" out of question, and to suggest a method which might make an experimental observation feasible.*

Pontecorvo chose the radiochemistry method (his experience in Rome with Fermi) to concentrate in a single small "place" for detection the few radioisotopes extracted from a large (cubic metres ...) irradiated volume.

The neutrino threshold for the process to take place is determined by either one of the following relations

- $(\nu + M_A^Z)c^2 + E_\nu > (m + M_A^{Z-1})c^2$ $[(\nu + p \rightarrow e^+ + n) \text{ reaction}]$
- $(\nu + M_A^Z)c^2 + E_\nu > (m + M_A^{Z+1})c^2$ $[(\nu + n \rightarrow e^- + p) \text{ reaction}]$

ν and m are the masses of the neutrino and electron, E_ν is the kinetic energy of the neutrino, M_A^Z , M_A^{Z-1} , M_A^{Z+1} the masses of the nuclei involved.

No explicit distinction is made across this article between neutrino and anti-neutrino. There is no practical way to observe electrons from neutrino interactions.

As to the properties of the material irradiated Pontecorvo suggested that:

- *It must be cheap (large quantity of material needed).*
- *The nuclei produced from the neutrino absorption must have a lifetime of at least several days, because of the long time involved in the chemical separation.*
- *The chemical separation of the radioactive atoms from irradiated material must be simple. The addition of only a few grams of non-isotopic carrier, per cubic meter of material treated, should give efficient separation.*
- *The smaller is the maximum energy of the electron emitted by the radio-isotope, the smaller is the mass difference between the two nuclei, and correspondingly the higher are the energy of the positron concomitant with the neutrino interaction and the energy of the neutrino impinging on the nucleon, whose cross section increases rapidly with the energy.*

Obviously the choice of the chemical compound of the element to be irradiated does not affect the physics of the inverse β process.

In P.D.-141 Pontecorvo only gives *an example*.

“There are several elements which could be used for neutrino irradiation in the suggested investigation. Chlorine, for example, fulfils reasonably well the desired condition indicated (above). According to Seaborg’s Table of Isotopes (Oct 1944) S_{16}^{35} is a β -active radioelement, decaying to Cl_{17}^{35} with a period of 87.1 days, the energy of the β -ray radiation being only 120 KeV. S_{16}^{35} would be produced by absorption of a neutrino and emission of a positive electron from the original Cl_{17}^{35} . According to Gueron (a Chalk River chemist), the best compound to irradiate from a chemical point of view would be CCl_4 (carbon tetrachloride).

A_{18}^{35} ($T=1.88$ s) also could be produced from Cl_{17}^{35} by absorption of a neutrino and emission of an electron: however, the disintegration leading to A_{18}^{35} is a priori much less probable than the one leading to S_{16}^{35} because the maximum energy of β -rays from A_{18}^{35} is as high as 4.4 MeV.”

The above data have been put together in the following table.

Chlorine 35 only

$\nu + Cl_{35}^{17} \rightarrow S_{35}^{16} + e^+$	S_{35}^{16}	$\tau = 86.7d$	β^-	0.167 MeV
$\nu + Cl_{35}^{17} \rightarrow A_{35}^{18} + e^-$	A_{35}^{18}	$\tau = 1.83s$	β^+	4.96 MeV

May I recall that in 1936, after their discovery of slow neutrons, the Fermi’s group spanned the whole Mendelejev table to search for new radioisotopes. The results were collected in a long table attached to the paper communicated by Rutherford to the Royal Society, London, essentially the forerunner of the long series of tables initiated by Seaborg. The only long life isotopes found were obtained by neutron interaction with Sulphur and Chlorine.

Pontecorvo then considered the mean free path of neutrinos against CCl_4 , that was a strong function of the neutrinos energy and the type of transition involved in the inverse β process. He considered improbable (Bethe and Bacher) a mean free path much smaller

than 10^{19} cm, although it might be orders of magnitude bigger. Assuming a mean free path of 10^{19} cm, the production of S_{16}^{35} would be observable by using a volume of the order of cubic meters and a radioactive source with an intensity of the order of 10^{17} neutrinos per second. It was Pontecorvo's opinion that such extremely intense source did not go much beyond the technical facilities of the time ("hot" metal from reactors).

Pontecorvo also considered possible "background effects" (of a different nature than effects induced by neutrinos via the inverse β process), which could produce the radioactive atoms looked for. A survey had shown that there should be no serious trouble if adequate care was taken and necessary control experiments were performed.

P.D.-141 ends with thanks to Maurice Pryce for very useful discussion and advice that Pontecorvo recalled in a final note:

"Dr. Pryce pointed out to the author that the flux of neutrinos from the sun is quite considerable. Actually, the flux of neutrinos received from the sun at the earth's surface may be estimated to be of the order of 10^{10} neutrinos/sec./cm.², providing Bethe's carbon cycle is assumed as source of energy of the sun.

This value is too low for an experiment of the type suggested. If sources of neutrinos other than the sun should produce on the earth's surface a flux as high as 10^{16} neutrinos/sec./cm.², the neutrinos would induce a radioactivity very slight - but measurable by the chemical concentration method - in a number of substances"

In the course of my visit to Chalk River in May 1997, having learned from Geoffrey Hanna of the previous Pontecorvo's interest for a possible Chlorine-35 \rightarrow Sulphur-35 experiment, I enjoyed discussing with him possible reasons why Pontecorvo only later considered a Chlorine-37 \rightarrow Argon-37 experiment.

The following table shows together the parameters for the neutrino interaction with Chlorine-35 and Chlorine-37 at the time Pontecorvo drafted P.D.-141.

Natural Chlorine, P.D.-141

$\nu + Cl_{35}^{17} \rightarrow S_{35}^{16} + e^+$	S_{35}^{16}	$\tau = 86.7d$	β^-	0.167 MeV
$\nu + Cl_{35}^{17} \rightarrow A_{35}^{18} + e^-$	A_{35}^{18}	$\tau = 1.83s$	β^+	4.96 MeV
$\nu + Cl_{37}^{17} \rightarrow S_{37}^{16} + e^+$	S_{37}^{16}	$\tau = 5.1min$	β^-	4.7 MeV
$\nu + Cl_{37}^{17} \rightarrow A_{37}^{18} + e^-$	A_{37}^{18}	$\tau = 34.3d$		

The case showing the energy of Argon-37 β radiation is empty.

After the discussion Hanna scribbled for me in his precise and clear handwriting a brief memoir:

“Ref 4 (the 1944 Seaborg’s table, in P.D.-141), dated January 1944, lists Ar-37 as having a 34-day half life, and cites Weimer, Kurbatov and Pool, *Phys. Rev.* 60, 469 (1941). It was detected by admitting it into a ionization chamber that provided no information on the nature of the radiation emitted. In a later paper, *Phys. Rev.* 66, 209 (1944), the same authors established that it decayed by K-capture using a cloud chamber and aluminium absorbers. Presumably Bruno was not aware of this later measurement when he wrote P.D.-141.”

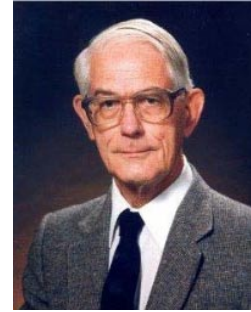


Fig. 1 G.C. Hanna

May I add a point of mystery to this story? The second paper by Weimer et al. [29] was accepted by *Physical Review* on May 14, 1942, and published two and a half years later, in the October 1 and issue 15 of *Physical Review*. The Weimer et al. first [30] paper had been accepted for publication hardly 8 months before. The first and the second paper were cited in the 1944 and 1948 editions, respectively, of the Seaborg’s Tables of Isotopes. As said earlier the P.D.-141 and the P.D.-205 reports were classified because the inverse β process allowed (in principle) to determine the power of nuclear reactors far away.

Pontecorvo clearly learned about the new results of Weimer et al., most likely working back from the 1944 Seaborg’s quotation while writing P.D.-205.

Next table shows the properties of the elements figuring in P.D.-205. Argon-37 now decays by K_e capture. The energy of the Auger electron is not shown. It had not been established with certainty yet. But for Pontecorvo all that is only again an example!

Natural Chlorine, P.D.-205

$\nu + Cl_{35}^{17} \rightarrow S_{35}^{16} + e^+$	S_{35}^{16}	$\tau = 86.7d$	β^-	0.167 MeV
$\nu + Cl_{35}^{17} \rightarrow A_{35}^{18} + e^-$	A_{35}^{18}	$\tau = 1.83s$	β^+	4.96 MeV
$\nu + Cl_{37}^{17} \rightarrow S_{37}^{16} + e^+$	S_{37}^{16}	$\tau = 5.1min$	β^-	4.7 MeV
$\nu + Cl_{37}^{17} \rightarrow A_{37}^{18} + e^-$	A_{37}^{18}	$\tau = 34.3d$	K_e	Auger electron

Summarizing, the extraction of the radioactive Argon from the large mass of carbon tetrachloride appears by far easier than the separation of Sulphur in a Chlorine-Sulphur experiment (apart from the intrinsic difficulties to handle very large quantities of material). In principle the separation of Argon, an inert gas, could be done just by boiling, without chemicals.

The long life of Argon 37 (34.3 days) fulfils reasonably well the conditions indicated by Pontecorvo.

Solar neutrinos, only considered in P.D.-141, are explicitly retained as possible neutrino sources in P.D.-205, giving the start to experiments with volumes progressively increasing, while new studies on the intensity of the solar source encouraged optimism. Pontecorvo, who initially considered volumes of the order of the cubic meter, studied later experiments with 40 m³ railway tank wagons in a Canadian Rockies tunnel (Hanna). R. Davis used for his experiment to discover the neutrino, several years later, 580 cubic meters of C_2Cl_4 (similar to CCl_4). But the transition from sulphur-35 to Argon-37 was certainly determined by the advantages of the inert gas.

Two years later Pontecorvo, with the solar experiment still in mind, as soon as the NRX reactor was operational produced samples of A_{37} by an (n,γ) reaction, with the

double purpose to study the detection of A_{37} from the radiation emitted and to measure the energy of Auger electrons, and with the idea to clarify the decay mode of A_{37} .

In the course of that work he discovered with D.H.W. Kirkwood and G.C. Hanna, [31] (independently of Curran et al.) the high-gain operation mode of proportional counters that allowed them to determine the energy of the Auger electrons and to see the L_e capture. The study of proportional counters was pursued later by Pontecorvo at Harwell [32] before his departure for the Soviet Union.

Fig. 2 shows the pulse height spectrum of the radiation emitted in the decay of A_{37} , as detected by a high-gain proportional counter, obtained with a pulse height analyzer (an instrument better known as “kicksorter”). The position of the larger and the smaller peak corresponds to an energy of 2800 eV and about 200 eV, respectively, corresponding to K_e - and L_e -capture. The authors give a preliminary explanation of the fact that though the energy of the two peaks is rather well determined the same statement does not apply to the relative intensity.

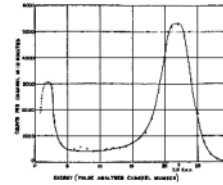


Fig. 2 Pulse height spectrum [32]

That result didn't appear in the 1948 Table of isotopes but completed P.D.-205, as shown in the following table.

Natural Chlorine, Auger 2.8 KeV

$\nu + Cl_{35}^{17} \rightarrow S_{35}^{16} + e^+$	S_{35}^{16}	$\tau = 86.7d$	β^-	0.167 MeV
$\nu + Cl_{35}^{17} \rightarrow A_{35}^{18} + e^-$	A_{35}^{18}	$\tau = 1.83s$	β^+	4.96 MeV
$\nu + Cl_{37}^{17} \rightarrow S_{37}^{16} + e^+$	S_{37}^{16}	$\tau = 5.1min$	β^-	4.7 MeV
$\nu + Cl_{37}^{17} \rightarrow A_{37}^{18} + e^-$	A_{37}^{18}	$\tau = 34.3d$	K_e	Auger 2.8 KeV

The high-gain proportional counters also allowed Pontecorvo and Hanna to record the β spectrum of tritium and to find that the neutrino mass had to be smaller than 500 eV (independently of Curran et al.).

Pontecorvo was very proud of his Chlorine-Argon method, but he never did the experiment. No railway tank wagon was ever filled with carbon tetrachloride and taken into a Canadian Rocky tunnel, as he moved to England. In Bristol he still computed cosmic-ray background with Camerini, but in September 1950 left for the Soviet Union where a large sychrocyclotron was waiting for him.

Raymond Davis, Jr., fascinated by the Pontecorvo's *Chlorine-Argon method*, (see his Nobel lecture) took over at BNL for life his method. In 1958 he found that reactors emit antineutrinos (the neutrino had just been discovered). A new experiment was then started by Davis and collaborators to detect solar neutrinos. It took several years to overcome the background. The Geiger counters were replaced with proportional counters and the pulse height measured, but that was not sufficient.

Pontecorvo met Davis at the first neutrino conference in Moscow in 1968 and expressed the opinion that *measuring the form of the counter pulse, in addition to the amplitude, should result in a considerable decrease of the effective background in his solar experiment*. The suggestion [32] proved correct as Pontecorvo found out from Davis at the ν '72 conference in Hungary. Thus the experiment *grace to the heroic effort of R. Davis, terminated brilliantly, but many years after its conception* [18].

In his *Note Autobiografiche* (1988-1989) [33] Pontecorvo wrote:

Confesso di essere piuttosto fiero del mio contributo personale alla nascita dell'astronomia solare neutrinica.



Бруно Понтекорво
... always smiling ...

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