The legacy of Bruno Pontecorvo: the Man and the Scientist

Roma, September 11–12, 2013 "Sapienza" University

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Bruno Pontecorvo and his Inverse β Process to Detect Neutrinos,

a page of history

(Giuseppe Fidecaro)

CERN

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Roma, *La Sapienza*, September 2013

from Bruno's Note Autobiografiche (1988-1989):

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

Among Bruno Pontecorvo highlights there is indeed the invention of the radiochemical methods to detect neutrinos.

But towards the end of his life Bruno estimated that his work had been unduly ignored
"...è un'ingiustizia ...perchè l'insieme dei miei lavori teorici e sperimentali ha avuto un'influenza decisiva ..."

Then let us go back in time

- **Bruno's inverse β process, known as Cl^{37}-A^{37} process, was described in 1946, in a lecture at a Nuclear Physics Conference organized for students by the National Research Council of Canada at McGill University.**
- **The lecture, issued as Report P.D.-205 of the National Research Council of Canada, Division of Atomic Energy, Chalk River, Ontario, 20 Nov. 1946, was immediately classified by the U.S. Atomic Energy Commission. It was declassified on Oct. 8, 1949.**
- **I got by mail a copy of the original in June 1996 from M. Harvey Director of the Physics Division of the Chalk River Laboratories.**
- **In the course of my visit to Chalk River in May 1997 I learned that in fact no Proceedings were published, only a few lectures.**

- **Pontecorvo's first idea had been a Cl^{35}-S^{35} process, as shown in his Report P.D.-141 dated May 21, 1945, also classified, apparently unknown to the physics community. Geoffrey C. Hanna, one of his close collaborators, sent me a copy of P.D.-141 on Oct. 24, 1996.**

- **In my previous recollections (published in 1997 in Bruno's *Selected Works* by the Italian Physical Society and by the Russian Academy of Science) I could only refer to P.D.-141 with a brief comment, for obvious reasons.**

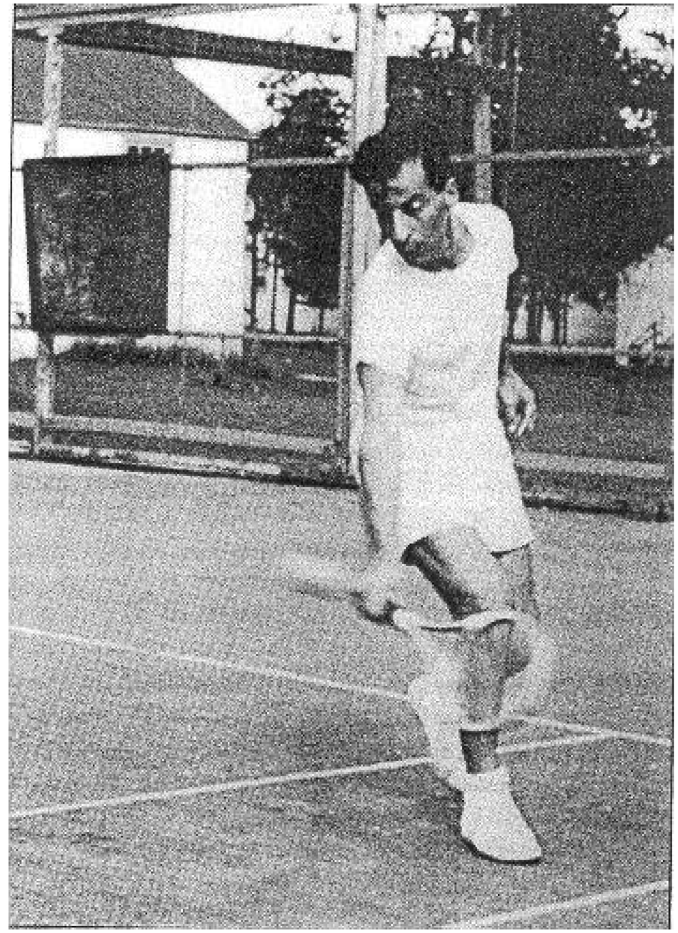
- **Pontecorvo started physics in Rome, we are in Rome, and Rome is the starting point of the talk.**

Moving to Rome

- **Born in Pisa, Bruno Pontecorvo was the son of an enlightened textile industrialist with a few hundred workers. The old factory building hosts today the Departments of Physics and Mathematics, at Largo Pontecorvo.**
- **Attracted by the Fermi's personality he moved to the University of Rome as third year physics student, after two years at Pisa as engineering student, obtaining his Laurea in physics in 1933. Only three years earlier Pauli had introduced the neutrino hypothesis.**
- **At the old Physics Institute in Via Panisperna he then joined the Fermi group, contributing to the experiments that led to the discovery of slow neutrons and of radioactivity by neutrons.**
- **In spring 1936, after the conclusion of the work, including a table of the new radioelements Bruno obtained a grant by the *Ministero dell'Educazione Nazionale* to spend time abroad.**

Moving to Paris on Fermi advice

- **At the Frédéric Joliot-Curie and the Irène Curie laboratories, following some theoretical ideas of his own, and working mostly alone, though enjoying advice from Joliot-Curie whom he considered as his second *maestro* after Fermi, Bruno did an impressive amount of work in the field of nuclear isomerism for which he got the Curie-Carnegie prize.**
- **Last (1939), working with A.Lazard he succeeded to produce β-stable isomers irradiating stable nuclei with high-energy X-rays, a new phenomenon named *nuclear fosforence* by F. Joliot. Fermi congratulated Bruno *per l'ottimo risultato della ricerca …Ed io che ero convinto che Fermi chiamandomi a Roma 'il gran campione' avesse un certo rispetto per me soltanto come esperto di tennis*! Bruno wrote.**



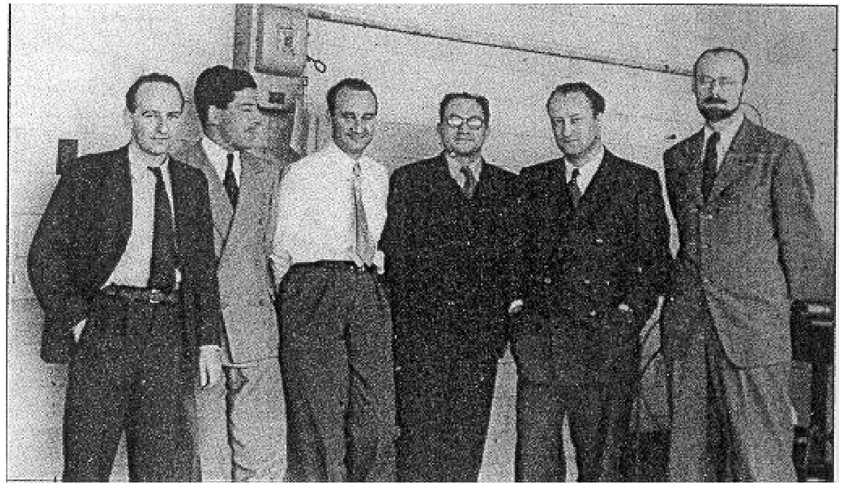
... Deep River 1948...

Moving to the United States

- **In summer 1940, leaving the war behind, after a difficult journey Bruno succeeded to reach the United States with his wife Marianne and his first son Gil. He got a job from a US firm, the Well Surveys Inc. at Tula, Oklahoma, interested in radioactivity well logging (carotaggio radioattivo).**
- **He got engaged himself in the development of a new geophysical well logging method. Helped by his Rome experience, he invented and set up the neutron well logging (carotaggio neutronico), then widely used in oil fields all over the world.**
- **A probe consisting of a strong neutron source, an ionization chamber with an amplifier, and a recording meter, is moved at constant speed (as large as possible) in a well.**
- **Neutron well logging was the first important application of neutrons. U.S. patents were issued to Bruno for his invention.**

Return to Research

- **Bruno only made very little money out of his invention. His interest in physics prevailed on several attractive offers for work in oil industry. He joined the Anglo-Canadian atomic project under H. von Halban in September 1942 at Montreal, where physicists well known to him already worked.**
- **Thus, very early in 1943 Bruno becomes a member of the British staff of the Montreal laboratory of the National Research Council of Canada, and moves with the family to Montreal, happy to be again in the stimulating environment of a research center.**
- **After the decision, under (Lord) John Cockcroft in middle 1944, to build a large heavy water and natural Uranium reactor *NRX (National Research eXperimental)*, we find Bruno in charge of several physics aspects of the reactor.**



... Montreal 1944 ...

from left, Henri Seligman, Bruno Pontecorvo, Bertrand Goldschmidt, Jules Guèron, Hans von Halban, Pierre Auger

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Until middle 1944 (arrival of John Cockcroft) the relations of the Montreal team with the US AEC were not always easy. Shortly afterwords most French scientists returned to France

- **In the period 1943-45 Bruno worked essentially on design problems writing some 25 reactor related reports, including work with design engineers on the shielding from mid-1944.**
- **In 1945-46 he worked on a large BF_3 neutron counter to detect fuel failures and, with (Lord) Brian Flowers and Dave Kirkwood, on the development of sensitive neutron monitors for the initial start-up of NRX (from ”zero” flux).**
- **The NRX reactor started operation on July 22, 1947. Designed as the most powerful research reactor it was opened to physicists, chemists, biologists, metallurgists competing for space and time.**
- **NRX became later, until it was shut down, one of the main suppliers of radioactive isotopes for medicine.**

... Chalk River September 1945 ...
ZEEP (1 W) becomes operational,
the first heavy water reactor outside USA
NRX is being constructed (on the back)

The NRX reactor started operation on July 22, 1947

Chalk River Laboratories

Chalk River Laboratories

Deep River before 1953

Hunting the invisible neutrino

- **A discrepancy had been observed in the early thirties when working with radio-active substances. The difference between the mass (i.e. the energy) of the mother and of the recoiling daughter nuclei was equal to the maximunm energy of the β spectrum, and didn't change, while the total energy of the two daughter particles changed (the β spectrum was continuous). There was a loss of visible energy in the disintegration.**
- **Two hypothesis were formulated , either the missing energy was taken away by a new totally invisible particle, the neutrino (Wolfgang Pauli), or the energy conservation law failed in the case of β decay (Niels Bohr). Inventing new particles required a good dose of courage at that time: *Dear radioactive ladies* ...**
- **Attempts were made to explain the phenomenon, but most people thought that looking for neutrinos did not make really sense.**

The Inverse β Process

- **β-radioisotopes do not exist in nature. They can be created by natural processes (i.e. radio-carbon 14) or artificially by nuclear reactions with stable nuclei. For example, a β-radioisotope decays into an electron and a neutrino, returning to its original status as stable nucleus (direct process). The inverse process consists in a radioisotope created by free neutrino interaction with stable nuclei and positron emssion. The inverse process is bound to exist. Detection of a radioisotopes is proof of neutrino existence.**
- **The neutrino cross-section was extremely small (less than 10^{-42} cm^{2} according to Fermi's theory) and it had been currently stated that it was impossible to observe such processes. Purpose of P.D.-141 note was *to show that the experimental observation of an inverse β process is "not" out of question, and to suggest a method which might make an experimental observation feasible.***

Principle of the method

- **Two problems: find sources of neutrinos and work out the method.**
- **NRX reactor was the source to be considered in the first place. It was there and had been designed as the most powerful research reactor at that time. Nuclear reactors were intense sources of neutrinos (antineutrinos, as it was found ten years later) and Bruno's knowkedge of reactor physics, in particular of the physics of NRX reactor, came in to help him.**
- **As to the method the problem was events against background, like in all cases when rare events have to be studied. His experience in Rome with Fermi suggested him to use the radiochemistry method. The essential point is that the radioactive atoms produced have different chemical properties. The few atoms produced can thus be extracted from the irradiated volume (cubic meters . . .) and concentrated in a single small "place" for detection.**

- **The inverse process is energetically possible if**
- $(\nu + M_A^Z)c^2 + E_\nu > (m + M_A^{Z-1})c^2$ **[(** $\nu + p \rightarrow e^+ + n$ **)** reaction**]**
- $(\nu + M_A^Z)c^2 + E_\nu > (m + M_A^{Z+1})c^2$ **[(** $\nu + n \rightarrow e^- + p$ **)** reaction**]**
- ν **and m are the masses of the neutrino and electron, E$_\nu$ is the kinetic energy of the neutrino, M$_A^Z$, M$_A^{Z-1}$, M$_A^{Z+1}$ the masses of the nuclei involved. There is a threshold for the reaction to take place.**
- **In P.D.-141 the neutrinos are Majorana neutrinos, as believed.**
- **The smaller is the maximum energy of the electron emitted by the radio-isotope, the smaller is the masss 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.**
- **No practical way to observe electrons from neutrino interactions.**

Properties of Material irradiated

- ***It must be cheap (large quantity of material needed).***
- ***The nucleus produced from the neutrino absorption must be radioactive with 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. It is necessary that the addition of only a few grams of non-isotopic carrier, per cubic meter of material treated, gives an efficient separation.***
- ***The maximum energy of the β-ray spectrum of the radioelement produced must be as small as possible ...***

Natural Chlorine

$\nu + Cl^{17}_{35} \rightarrow S^{16}_{35} + e^{+}$
$\nu + Cl^{17}_{35} \rightarrow A^{18}_{35} + e^{-}$
$\nu + Cl^{17}_{37} \rightarrow S^{16}_{37} + e^{+}$
$\nu + Cl^{17}_{37} \rightarrow A^{18}_{37} + e^{-}$

S^{16}_{35}	$\tau = 86.7d$	β^{-}	0.167 MeV
A^{18}_{35}	$\tau = 1.83s$	β^{+}	4.96 MeV
S^{16}_{37}	$\tau = 5.1min$	β^{-}	4.7 MeV
A^{18}_{37}	$\tau = 34.3d$		

- **Natural Chlorine, mixture of Cl$_{35}$ (75%) and Cl$_{37}$ (25%)**
- **G.T. Seaborg's Table of isotopes, Oct 1944: Chlorine chosen.**
- **Hint from Rome 1936 mini-table? Cl and S only long-life isotopes**
- **Carbon tetrachloride $C\,Cl_4$ most convenient chemical compound**
- **Reactor v/s solar neutrino flux, discussion with M.Pryce, footnote**

Chlorine-Sulphur

$\nu + Cl^{17}_{35} \rightarrow S^{16}_{35} + e^{+}$
$\nu + Cl^{17}_{35} \rightarrow A^{18}_{35} + e^{-}$

S^{16}_{35}	$\tau = 86.7d$	β^{-}	0.167 MeV
A^{18}_{35}	$\tau = 1.83s$	β^{+}	4.96 MeV

Chemical separation not practical for very large volumes

Status after P.D.-141 issued

- **As to the extraction of the radioisotope from the large mass of carbon tetrachloride, the separation of Argon, an inert gas, is much easier than the separation of Sulphur. The separation of Argon could be done just by boiling, without chemicals.**
- **The long life of Argon 37, 34.3 days, fitted well the expectation.**
- **As to the decay mode of Argon 37, new results became available. These results, received for publication in May 1942, were only published two and a half years later, in the October 1944 issue of the Reviews of Modern Physics. Missed by Seaborg in 1944, they were also missed by Pontecorvo in 1945. They only appeared in the 1948 issue of the Table of isotopes.**
- **It was found that Argon 37 returned to the state of Chlorine by K_e capture emitting an Auger electron whose energy had not been estalished with certainty.**

- **Pontecorvo clearly learned about the existence of these new results, probably by working back from a quotation in the 1944 issue of the Table of isotopes. These results were in fact incorporated in his 1946 lecture issued 25 November 1946, the Report P.D.-205.**

Natural Chlorine

$\nu + Cl^{17}_{35} \rightarrow S^{16}_{35} + e^{+}$
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S^{16}_{37}	$\tau = 5.1min$	β^{-}	4.7 MeV
A^{18}_{37}	$\tau = 34.3d$	K_e	Auger electron

- **P.D.-205 neutrinos are still Majorana neutrinos ...**
- **Solar neutrinos are considered as neutrino source in P.D.-205. Probably the move from Sulphur to Argon opened the way to experiments using very large volumes of Chlorine compounds. Pontecorvo was in fact working on an experiment using 40 m^3 railway tank wagons in a Canadian Rockies tunnel (Hanna).**

- **With the solar experiment still in mind, as soon as the NRX was operational Pontecorvo produced samples of A$_{37}$ by a (n,γ) reaction, with the double purpose to prepare a proportional counter to measure the energy of Auger electrons, and to clarify the decay mode of A$_{37}$.**
- **Thus he discovered the high gain mode of operation of proportional counters that allowed him to determine the energy of the Auger electrons (= 2.8 KeV) and see the K$_l$ capture). That result didn't appear in the 1948 Table of isotopes but completed P.D.-205.**

$\nu + Cl^{17}_{35} \rightarrow S^{16}_{35} + e^{+}$
$\nu + Cl^{17}_{35} \rightarrow A^{18}_{35} + e^{-}$
$\nu + Cl^{17}_{37} \rightarrow S^{16}_{37} + e^{+}$
$\nu + Cl^{17}_{37} \rightarrow A^{18}_{37} + e^{-}$

Natural Chlorine

S^{16}_{35}	$\tau = 86.7d$	β^{-}	0.167 MeV
A^{18}_{35}	$\tau = 1.83s$	β^{+}	4.96 MeV
S^{16}_{37}	$\tau = 5.1min$	β^{-}	4.7 MeV
A^{18}_{37}	$\tau = 34.3d$	K$_e$	Auger 2.8 KeV

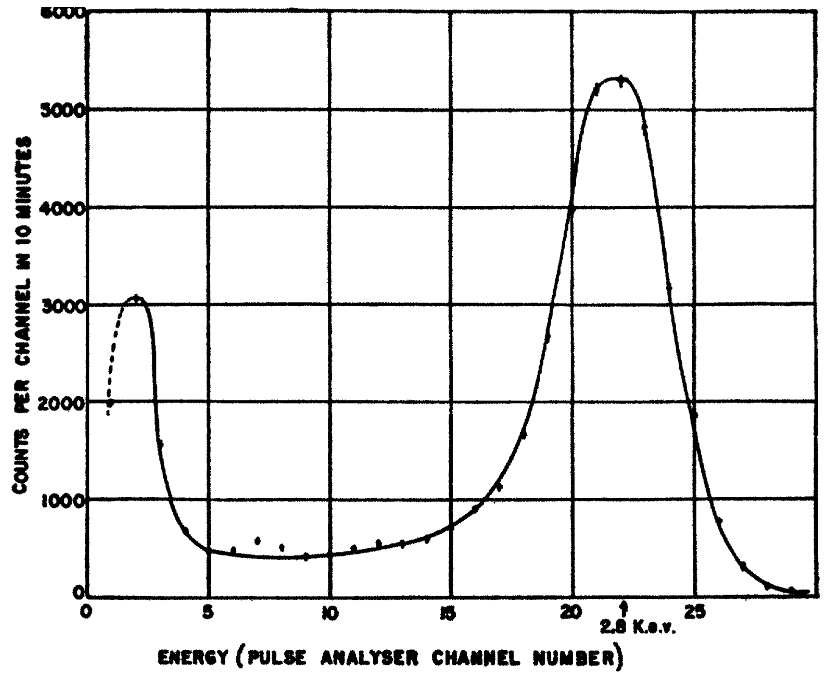
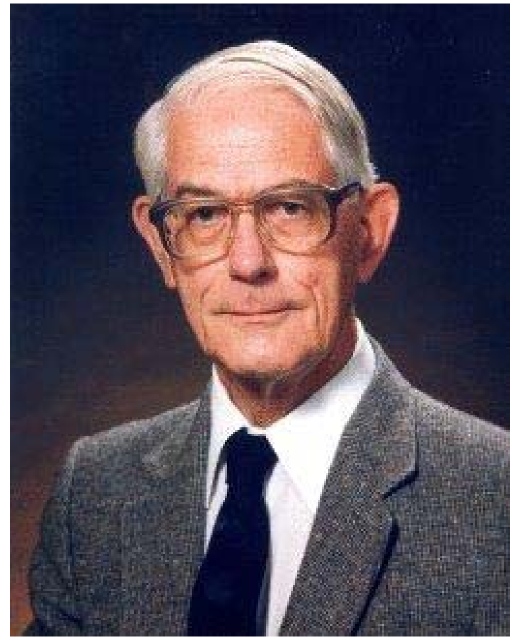


FIG. 1.

D. H. W. Kirkwood, B. Pontecorvo, and G. C. Hanna

Phys. Rev. 74 (1948) 497

Geoff C. Hanna 

Bruno developed with him and D.H.W. Kirkwood high gain proportional detectors to register the radioactive argon nuclei resulting from the neutrino reactions. By introducing tritium produced in the NRX reactor in their counter he also found with him that the neutrino mass had to be smaller than 500 eV.

- **Concluding, the original choice Cl_{35}-S_{35} in P.D.-141 (1945), rather than Cl_{37}-A_{37}, was determined by the confusing status of the available Cl_{37} data.**
- **The P.D.-205 report (1946) was based on the choice of Cl_{37}-A_{37} method after Pontecorvo found the new A_{37} data in the literature. Those data didn't report unambiguously the energy of the Auger electron. The energy of the Auger electron was in fact sistematically ignored in the P.D.-205 text.**
- **The Cl_{37}-A_{37} method only acquired full shape in 1948, after Pontecorvo fully clarified the A_{37} decay mode by recording the β-spectrum of A_{37} gas introduced in a high-gain proportionl counter, and measured the energy of the Auger electron (also observing K_l capture).**

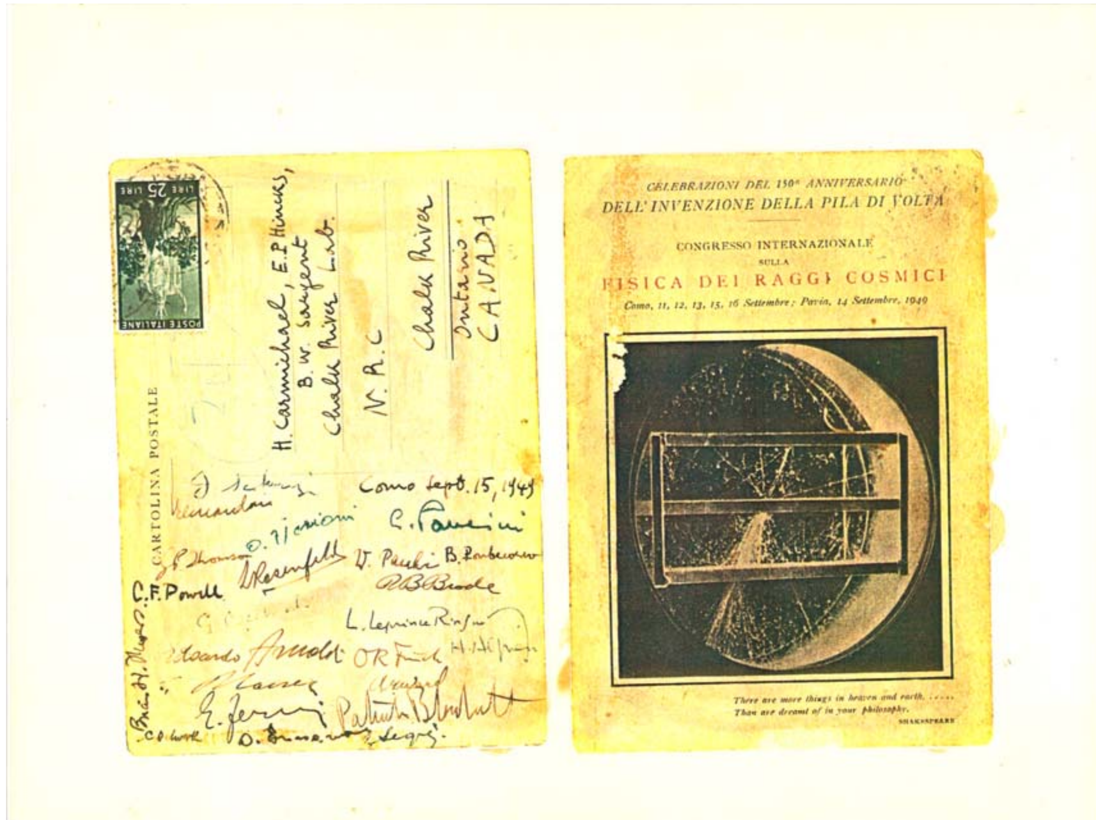
- **Pontecorvo was very proud of his Chlorine-Argon method, but he never did the experiment. No railway tank wagon was ever filled with carbon tetrachloride and taken into a Canadian Rocky tunnel as he moved to England. In Bristol he computed cosmic-ray background with Camerini, then left for Dubna where a large sychrocyclotron was waiting.**
- **Raymond Davis was fascinated by the *Pontecorvo Chlorine-Argon method* and spent all his life at BNL working with that method. In 1958 he found that reactors emit antinutrinos (the neutrino had just been discovered). In 1968 measured the solar flux. (See Davis Nobel lecture)**

from left, Bruno Pontecorvo, Antonio Rostagni, Enrico Fermi visiting the premises of the Olivetti firm in Ivrea, at the time of Basel/Como Conference (September 1949)

There are more things in heaven and earth
that you can dream in your philosophy (Shakespeare)

... Como, September 1949 ...

a postcard sent to H. Carmichael, E.P. Hincks, B.W. Sargent
signed J. Schwinger, Bernardini, O. Piccioni, E. Pancini, J.P. Thompson,
C.F. Powell, L. Rosenfeld, W. Pauli, B. Pontecorvo, R.B. Brode
G. Occhialini, L. Leprince-Ringuet, Edoardo Amaldi, O.R. Frisch, H. Alfvén,
E. Fermi, Patrick Blackett, C. Dilworth, E. Segre, Brian H. Flowers



... Como, September 1949 ...

... always smiling ...