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Colloquia: The Legacy of Bruno Pontecorvo

The early years of Bruno Maximovich Pontecorvo at Dubna

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Summary. — At the beginning of September 1950, while on a short vacation in Italy with his family, Bruno Pontecorvo suddenly disappeared. Nobody knew of him until 4th March 1955, when he gave a press conference in Moscow at the Academy of Sciences where he explained the motivations that had led him to decide to live in Russia.
He arrived in Moscow in September 1950 and at the end of October of the same year he moved in Dubna and started his research work at the Institute of Nuclear Problems where, at the time, the most powerful particle accelerator in the world was in operation.
A historical reconstruction of the early years of his scientific activity is done through the pages of his first logbook. This "laboratory notebook", dated November 1, 1950, contains unpublished notes, ideas and considerations that Bruno wrote by hand, mostly in English, at the beginning of his work in Russia.

Several events have been organized in Italy to commemorate the centenary of the birth of Bruno Pontecorvo. In particular an exhibition [1] on the life and the scientific work of this great Italian physicist of the 20th century has been opened in Pisa in the seat of the Cultural Association La Limonaia-Scienza Viva, from November 9 to December 22, 2013. The exhibition *"Da Pisa a Mosca, un lungo viaggio attraverso storia e scienza"* ("From Pisa to Moscow, a long journey through history and science") includes testimonies and original documents, some unpublished, on the life and the long scientific work of Pontecorvo who gave a decisive contribution to the development of modern physics with revolutionary insights.

One of these documents is a logbook (Figure 1) with notes, ideas and considerations that Bruno wrote by hand, mostly in English, during his first years of work at the Institute of Nuclear Problems in Dubna. This unpublished document is particularly interesting because still today little is known of the scientific work of Pontecorvo during his first five years in Russia. This document was given from Gil Pontecoro, the oldest son of Bruno, to Gloria Spandre and Elena Volterrani both curators of the exhibition in Pisa, on the occasion of their visit to JINR in Dubna.

In preparing my talk to this Conference, I had the pleasure to read and to study this logbook which is extremely interesting because it provides a historical reconstruction of the early years of the scientific activity of Bruno Pontecorvo in Russia.

At the beginning of September 1950, while on a short vacation in Italy with his family, Pontecorvo suddenly disappeared. Nobody knew of him, his wife and his three children until 4th March 1955, when he gave in Moscow a press conference at the Academy of Sciences where he explained the motivations that had led him to leave the West and work in the Soviet Union. The next day, the international press, and in particular the daily l'Unità, gave great prominence to the news. In many newspapers Pontecorvo was depicted as the Italian scientist who passed the secrets of the atomic bomb to the Soviets and collaborated to the construction of the Russian hydrogen bomb. Nothing could be further from the truth, as Bruno himself several times repeated in many occasions.

In this logbook there is the proof that Bruno Pontecorvo has never worked or contributed to the Russian atomic bomb but he has only performed basic research in elementary particle physics. Let's proceed with order.

Bruno arrives in Moscow in September 1950 at the age of 37 years. At the end of October of the same year he moves with his family in Dubna where, from December 1949, a synchrocyclotron, at the time the most powerful particle accelerator in the world, is in operation at the Institute of Nuclear Problems.

Who is Bruno Pontecorvo as a man and as a scientist when he decides to give up everything and to go to live in Russia? Which are the reasons for taking this drastic decision? A decision that will change irrevocably not only his life but also that of his wife and children.

It is certainly an experimental physicist with extensive experience of the most advanced particle detectors and at the same time he is a theoretical physicist with a deep knowledge of the theoretical ideas that are being developed on elementary particle physics.

He is also a convinced communist, who firmly believes in the possibility to realize a true socialist society based on a deep sense of justice and equality.

There is nothing surprising in this decision. Indeed Pontecorvo should have been excited to work at the most powerful particle accelerator in the world and, foremost, to live in a society that proclaims to build communism.

The reputation of brilliant assistant of Fermi precedes him and inspires great enthusiasm among the physicists of the Laboratory. It is customary among colleagues in the lab to call each other with name and patronymic therefore Bruno is renamed Bruno Maximovich, because his father's given name is Massimo. From that moment on, he will be Bruno Maximovich in all the scientific and social clubs of Russia.

Bruno starts working in the Dubna laboratory on November 1, 1950. In the first page of his notebook (Figure 2) under this date written in Russian, he writes, in English, his first consideration on how it might be possible to evaluate the energy of the neutron beam of the Dubna cyclotron (*"Neutron production by cyclotron particles"*).

In the following nine pages he annotates ideas about which experiments can be performed at that accelerator and which particle detectors have to be used. A few days later he stops writing in the logbook and only on September 14, 1951, he resumes writing by turning upside down the notebook and beginning from the last page: the page number 100 (Figure 3).

He has finally decided the experiment he wants to do. He is now a respected leader of a small group of young physicists and engineers. His first experiment is the study of pions production (π mesons) with neutron beams. *"Experiment on production of mesons by neutrons"* is the title just under the date September 14, written in Russian. He continues writing the page by describing in detail the experimental set-up.

In the next pages, up to the end of the notebook and without further interruptions, he

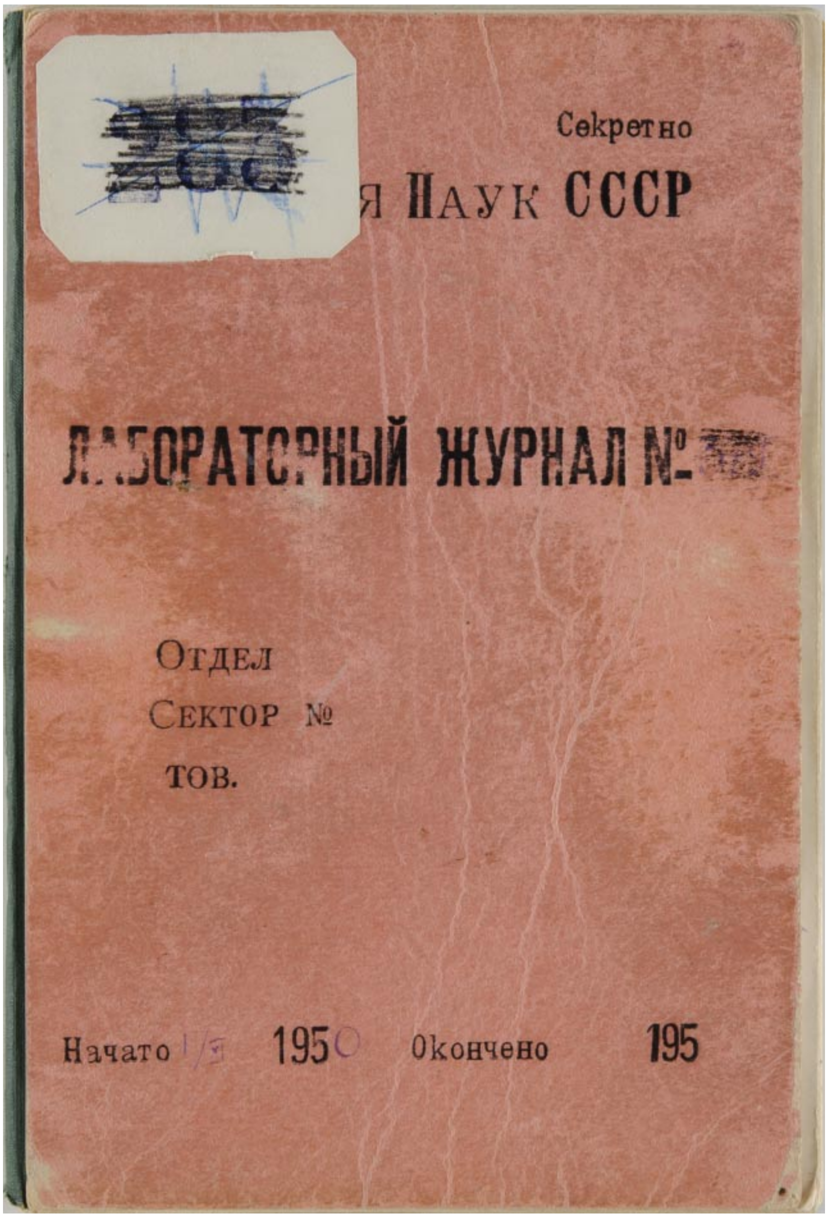
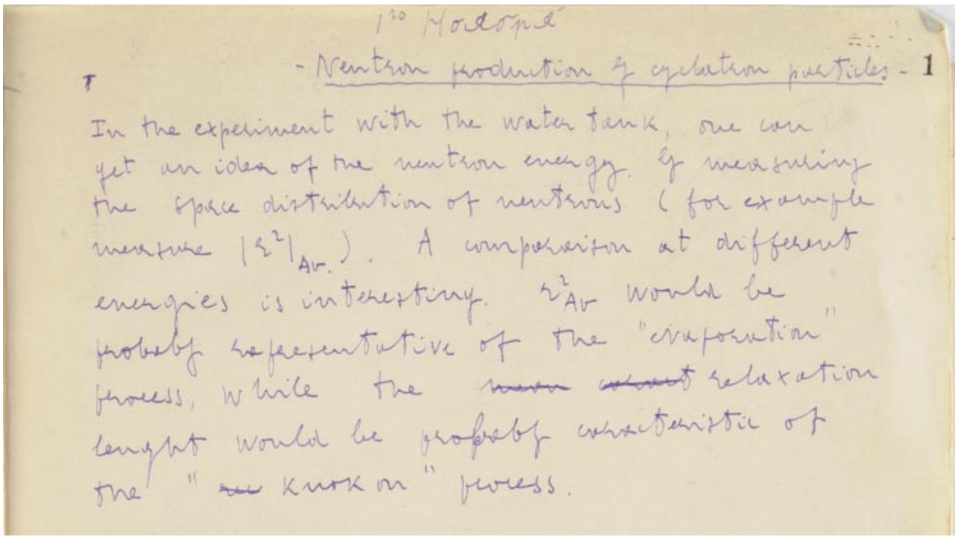


Fig. 1. – The Pontecorvo Logbook. The cover is bearing the date: I/XI 1950.

annotates the scientific work of his group and reports daily progress of this and other subsequent experiments. He takes note of data taking and measurements, and comments the results of the data analysis. He also writes drafts of articles that will be published in Russian as internal reports of the laboratory.

The last date written on the notebook is March 24, 1952, a few pages before the end. With the page number 9, that was partially written in November 1950, Pontecorvo ends


- Neutron production by cyclotron particles - 1

In the experiment with the water tank, one can get an idea of the neutron energy by measuring the space distribution of neutrons (for example measure $|r^2|_{Av.}$). A comparison at different energies is interesting. r^2_{Av} would be probably representative of the "evaporation" process, while the ~~mean~~ ~~about~~ relaxation lenght would be probably characteristic of the "knock on" process.

Fig. 2. – The first page begins with: *"Neutron production by cyclotron particles."*

his notes on the logbook.

With the Dubna accelerator which can accelerate protons up to an energy of 460 MeV, and alpha particles up to 560 MeV, protons and neutrons beams can be obtained. With such beams it is possible to study the properties of pion-nucleon interaction when neutral and charged pions are produced in nucleon-nucleon collisions on targets of hydrogen or complex nuclei. The interest in the production of pions with neutron beams, as Pontecorvo points out in the first paper of this first experiment, is due to the fact that many experiments, at that time, had been already done on pions production with proton beams but little or nothing it had been done with neutron beams. This experiment and other experiments, performed between 1951 and 1955, confirmed that the proton and the neutron, which are different particles for what concerns the electromagnetic interaction, due to their electrical charge, are not different as regards the strong interaction. Proton and neutron are essentially the same particle in two different states of a new quantum number called isotopic spin.

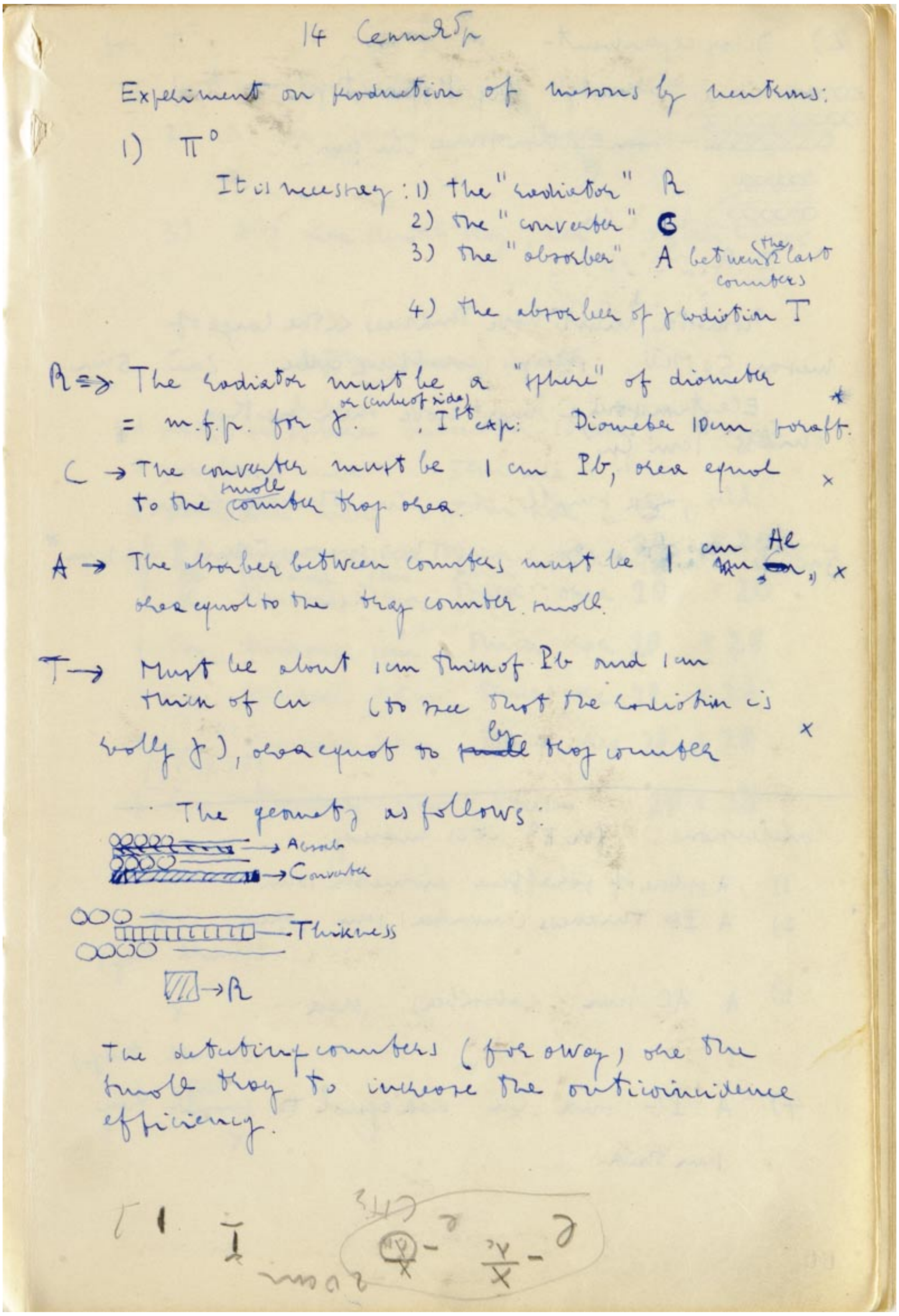
From the logbook pages it comes out the figure of a young scientist who coordinates the experiments and the activities of his group with expertise and scientific rigour. In frequent meetings he defines the experimental program and assigns tasks to all the members of the group (Figure 4):

1) *Vladimir + Anatol. Alex.: Finish work on the* H^4 *experiment in the present version + report;*

2) *Adolph: Finish work on mesons with radioactive indicators + report;*

3) *George: Finish work on duty factor + report... etc...*

Often he describes how to do tests and measurements and how to check the efficiency of the detectors; he takes note of the requests of working hours to the workshop and of the hours obtained to build the mechanical supports of the detectors; he reports the


14 Сентября

Experiment on production of mesons by neutrons:

1) π^0

It is necessary: 1) the "radiator" R
2) the "converter" C
3) the "absorber" A between the last counters
4) the absorber of γ radiation T

R ⇒ The radiator must be a "sphere" (or cube of side) of diameter = m.f.p. for γ. I^st exp: Diameter 10 cm for a ff.

C → The converter must be 1 cm Pb, area equal to the small counter tray area.

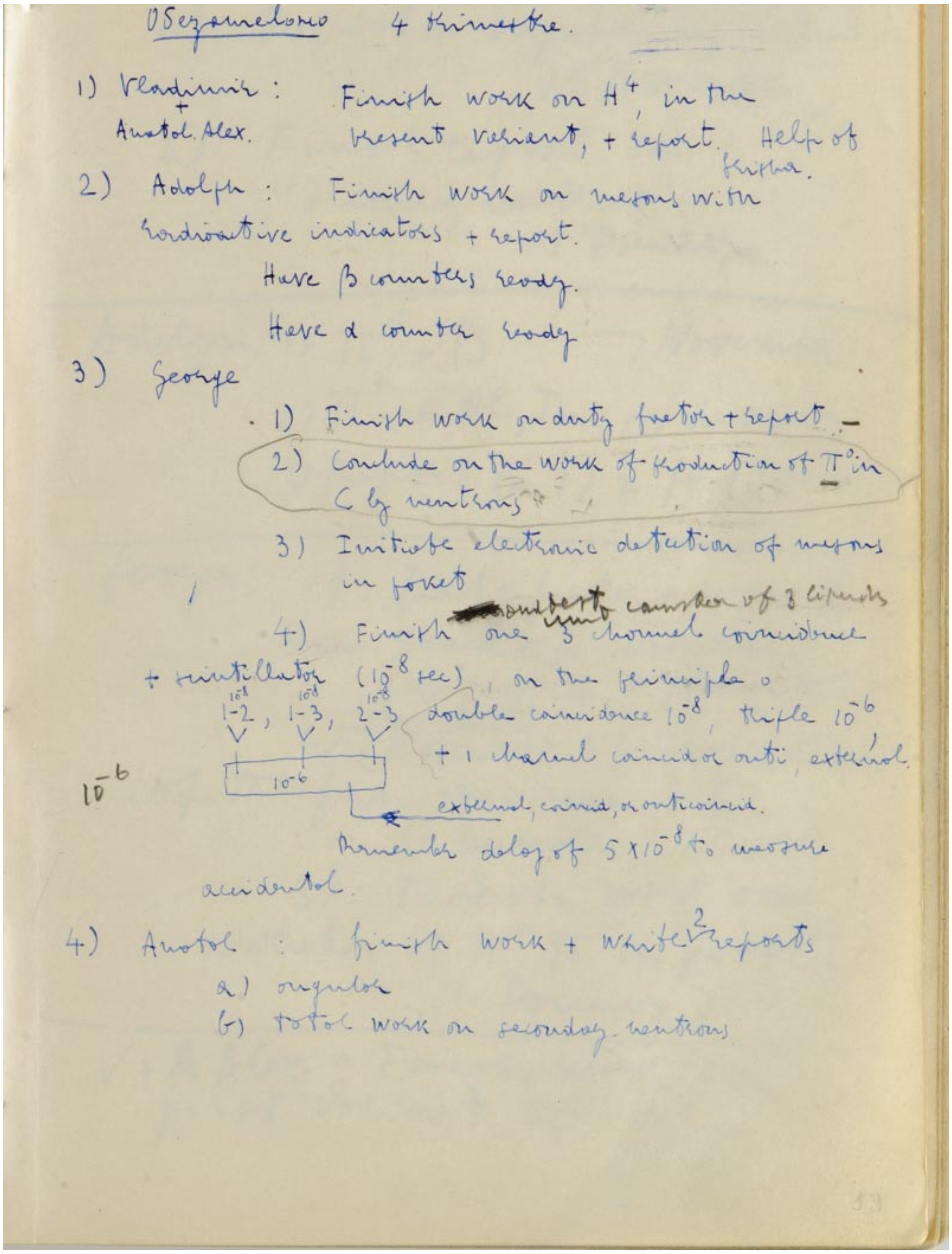
A → The absorber between counters must be 1 cm Al, area equal to the tray counter small.

T → Must be about 1 cm thin of Pb and 1 cm thin of Cu (to see that the radiation is really γ), area equal to big tray counter

The geometry as follows:

The detecting counters (far away) are the small tray to increase the anticoincidence efficiency.

Fig. 3. – September 14 (1951): *"Experiment on production of mesons by neutrons"*.


4 trimestre.

1) Vladimir + Anatol. Alex. : Finish work on H^4, in the present variant, + report. Help of Feriha.

2) Adolph : Finish work on mesons with radioactive indicators + report.

Have β counters ready.

Have α counter ready

3) George

1) Finish work on duty factor + report

2) Conclude on the work of production of π^0 in C by neutrons

3) Initiate electronic detection of mesons in forest

4) Finish one 3 channel coincidence counter of 3 liquids + scintillator (10^{-8} sec), on the principle o

1-2, 1-3, 2-3 double coincidence 10^{-8}, triple 10^{-6}

+ 1 channel coincid or anti, external.

10^{-6}

external, coincid, or anticoincid.

Remember delay of 5×10^{-8} to measure accidental.

4) Anatol : finish work + write 2 reports

a) angular

b) total work on secondary neutrons

Fig. 4. – Some remarks on the work of his group.

counts taken in the experiment and he draws tables of the final results. Finally he writes the report of the experiment.

The draft *"Production of neutral mesons by neutrons"* concerns the study of the production of π^0 mesons by a neutron beam on hydrogen or complex nuclei (Figure 5). This is a draft of an internal report [2] of the laboratory written in Russian, a copy of which, dated September 25, 1952, has been found by Gil Pontecorvo on the shelves of the JINR library. The paper was published again in 1955 [3].

Particularly interesting to understand how the young "leader" coordinates the work of his group is what he writes in preparation of the meeting of March 6, 1952 (Figure 6): *"In my opinion personal relations inside our group were not satisfactory"*. Pontecorvo, in a gentle but peremptory way, rebukes severely his smart and ambitious young colleagues who do not collaborate with each other: *"There were many examples where members of our group, for example, went for advice in electronics to other group, while there exists in our group a very well qualified man in electronics G.I."*. He concludes firmly: *"the situation was not satisfactory and we must change it radically for the interest of the total scientific production of the group"*.
Pontecorvo considers a very important issue a good collaboration among the team members, in particular between the expert in electronics and the physicists. For this reason he writes a document on how the problem must be solved. The draft of this paper is written on a separate sheet and inserted between the pages of the notebook. He writes: *"The specialization in science and techniques today is a necessity, however unpleasant it may be"*. He suggests the creation of a group of specialists to develop the electronics for all the experimental groups of the laboratory. He then adds that this solution can work only if it is guaranteed by *"... absolute equality of status between the profession in electronics and the profession on nuclear physics"*. Nowadays this problem is still not solved. Indeed it is a problem even more serious because of the increasing of technical complexity of experiments and electronics. It extends also to the experts in hardware and software. Pontecorvo could look far in the future also in this social and psychological aspect!

Another interesting page, written in Italian, is one in which Pontecorvo lists formulas and calculations that he is probably going to discuss in a lesson of physics to his young collaborators (Figure 7): *"Give approximate formulas for: 1) Masses in MeV (for) e (electron), π meson, μ meson, p (proton), D (deuteron). 2) Relation between momentum (MeV/c), Total energy (in MeV), Kinetic energy (MeV), β (v/c). 3) How to find β, momentum, KE, Total energy when it is known the particle mass and one of these quantities..."*.

In the next three pages he writes a list of relativistic kinematics formulas and reports the results of the calculation of the mean free path for protons and deuterons in copper and aluminum for different values of energy of these particles.

From the very beginning we see the teaching vocation of Pontecorvo which led him to be professor of elementary particle physics; one of the most beloved and respected professor of the Moscow University. Many of his students are today internationally renowned physicists.

The scientific interest of Pontecorvo goes far beyond the scattering experiments of nucleons and π mesons on nuclei, although important. Many of his reflections of these years still concern the weak interaction physics and the study of the so-called *strange* particles. Pontecorvo has always been fascinated by the weak interaction and has given fundamental contributions to its understanding.

In 1947, shortly after the famous experiment of Conversi, Pancini and Piccioni [4] and

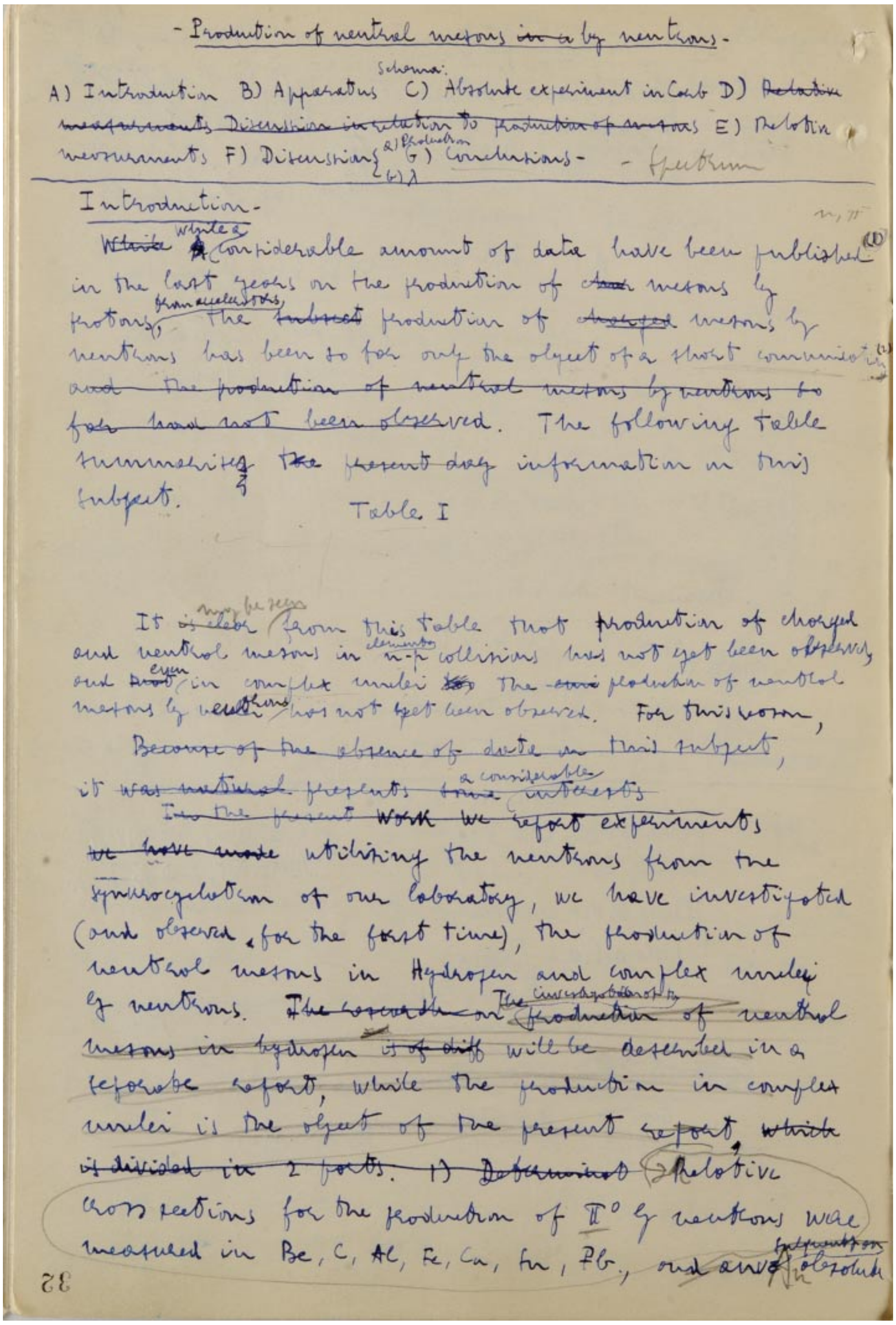
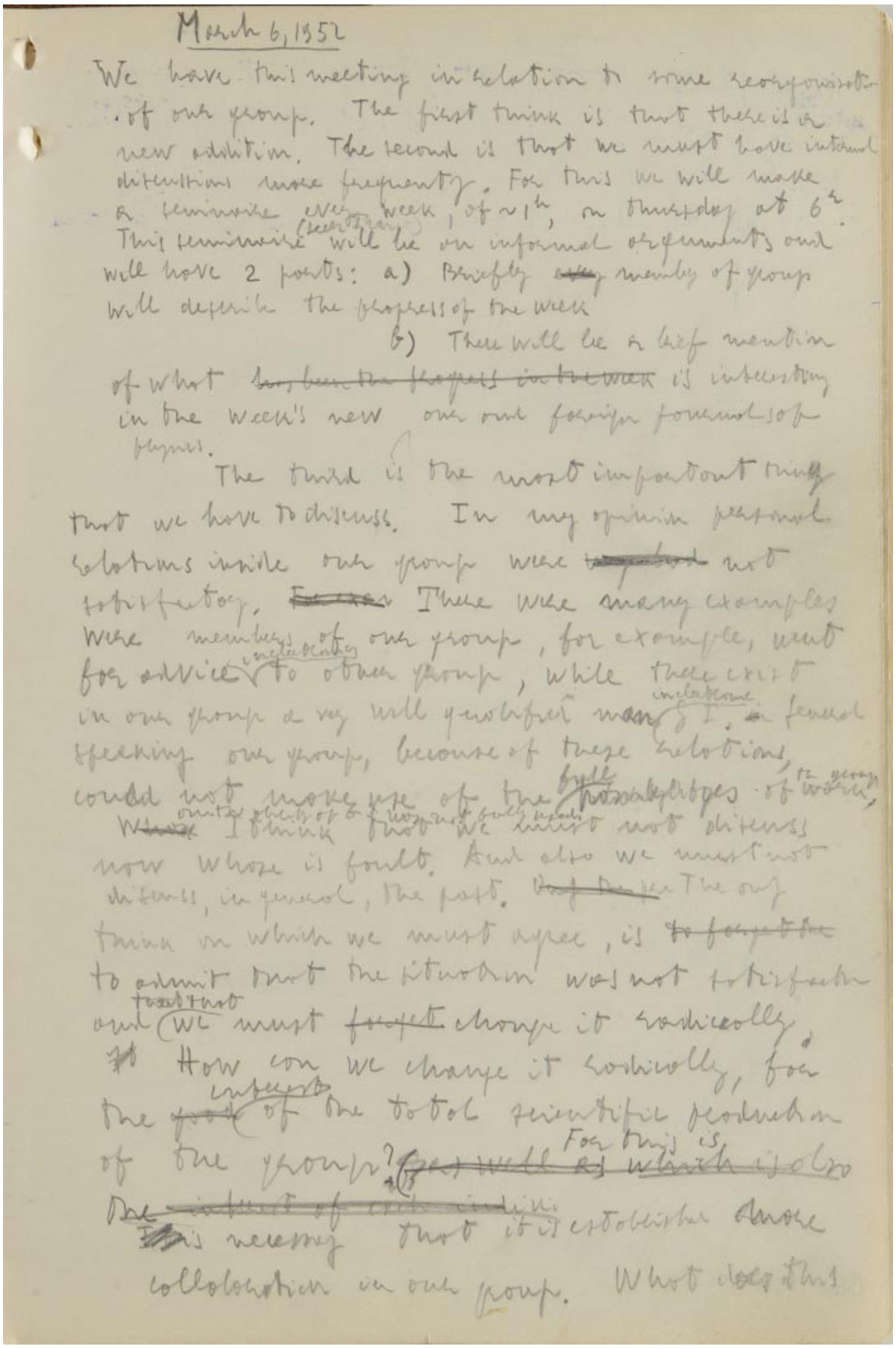


Fig. 5. – Draft of the first paper on *"Production of neutral mesons by neutrons"*.


March 6, 1952

We have this meeting in relation to some reorganisation of our group. The first thing is that there is a new addition. The second is that we must have internal discussions more frequently. For this we will make a seminar every week, of ~1h, on Thursday at 6h. This seminar (scientific) will be on informal arguments and will have 2 parts: a) Briefly every member of group will describe the progress of the week

b) There will be a brief mention of what ~~has been the progress in the week~~ is interesting in the week's new own and foreign journals of physics.

The third is the most important thing that we have to discuss. In my opinion personal relations inside our group were ~~[illegible]~~ not satisfactory. ~~[illegible]~~ There were many examples where members of our group went for advice (in laboratory) to other group, while there exist in our group a very well qualified man [illegible]. In general speaking our group, because of these relations, could not make use of the full possibilities of work [illegible]

~~Where~~ I think that we must not discuss now whose is fault. And also we must not discuss, in general, the past. ~~[illegible]~~ The only thing on which we must agree, is ~~to forget the~~ to admit that the situation was not satisfactory and (to ask that) we must ~~forget~~ change it radically.

How can we change it radically, for the ~~good~~ interests of the total scientific production of the group? ~~as well as which is also the interest of each [illegible]~~ For this is necessary that it is established more collaboration in our group. What does this

Fig. 6. – March 6, 1952: minutes of the group meeting.

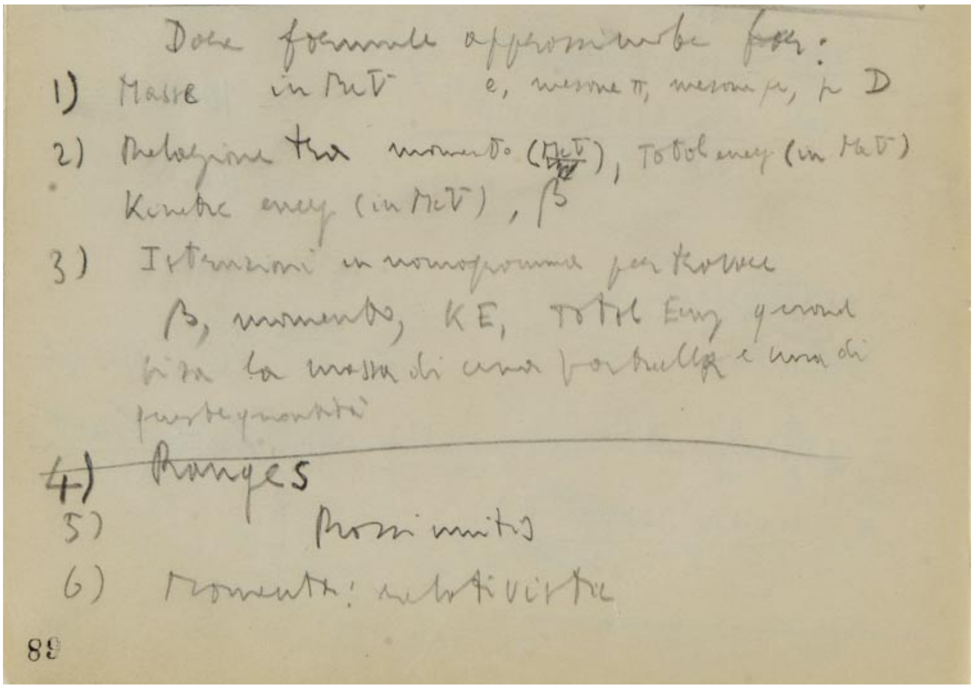


Fig. 7. – Notes for a physics lesson.

its interpretation by Fermi, Teller and Weisskopf, it was clear that the mesotron (now called muon) produced in cosmic rays and discovered by Anderson and Neddermeyer in 1937, was not the Yukawa particle (pion) that interacts strongly. The muon interacts much weaker with the nucleons. After reading the article by Fermi and collaborators, *"The decay of negative mesotrons in matter"* [5], Pontecorvo publishes in Physical Review the paper *"Nuclear capture of mesons and mesons decay"* [6]. In this article Pontecorvo observes that the probability of nuclear capture of an electron and a muon are practically identical (if account is taken of the large factor due to kinematic effects that depends from the mass difference of the two particles). Pontecorvo concludes by saying: *"there exists fundamental analogy between β-processes and processes of emission and absorption of charged mesons"*. Pontecorvo is the first to conceive the idea of muon-electron universality. This idea is the base of the whole theory of weak interactions.

No wonder if in the early fifties, when Pontecorvo arrives in Dubna, he has a strong interest in the behavior of the *strange* particles. These unstable particles, discovered in experiments with cosmic rays [7], are produced with high probability, typical of strong interactions, but decay with relatively long lifetimes (10^{-8} – 10^{-10} s), suggesting that the weak interaction is responsible for their decay. Why these particles, which are created by strong interaction in high-energy collisions of cosmic rays with nuclei in the atmosphere, do not decay with lifetimes typical of the strong decays?

To solve this problem A. Pais suggests in 1952 that strange particles such as the K meson and the Λ^0 hyperon should be likely produced in pairs. This process would be explained by the existence of a new quantum number, afterwards called strangeness, which is conserved in strong interactions but not in weak interactions. In those years also

Pontecorvo predicts, with simple arguments and independently from Pais, the production in pairs of Λ hyperons and K heavy mesons, as confirmed by V.P. Dzhelepov, the director of the Dubna laboratory.

Pontecorvo formulates the hypothesis of associated production in a paper published 1955. In this article he refers to some previous internal reports [8] and, in fact, on the page 8 of his logbook (Figure 8), written shortly after November 1, 1950, two years before the article by Pais, Bruno Pontecorvo writes: "…there is a contradiction between the existence of a strong interacting particle, and its long lifetime. This contradiction, of course, is resolved if the strongly interacting particle is produced in pair."

In 1953 Bruno performs an experiment at the Dubna accelerator to check if the hypothesis is true; namely, that it is not possible to produce single Λ^0 hyperons in strong interactions between protons and nucleons, being the energy of the accelerator not enough to produce them in pair with the K mesons. The results of the experiment on *"The possibility of the formation of Λ^0-particles in collisions of 670 MeV protons with carbon nuclei"* [9], confirmes his hypothesis.

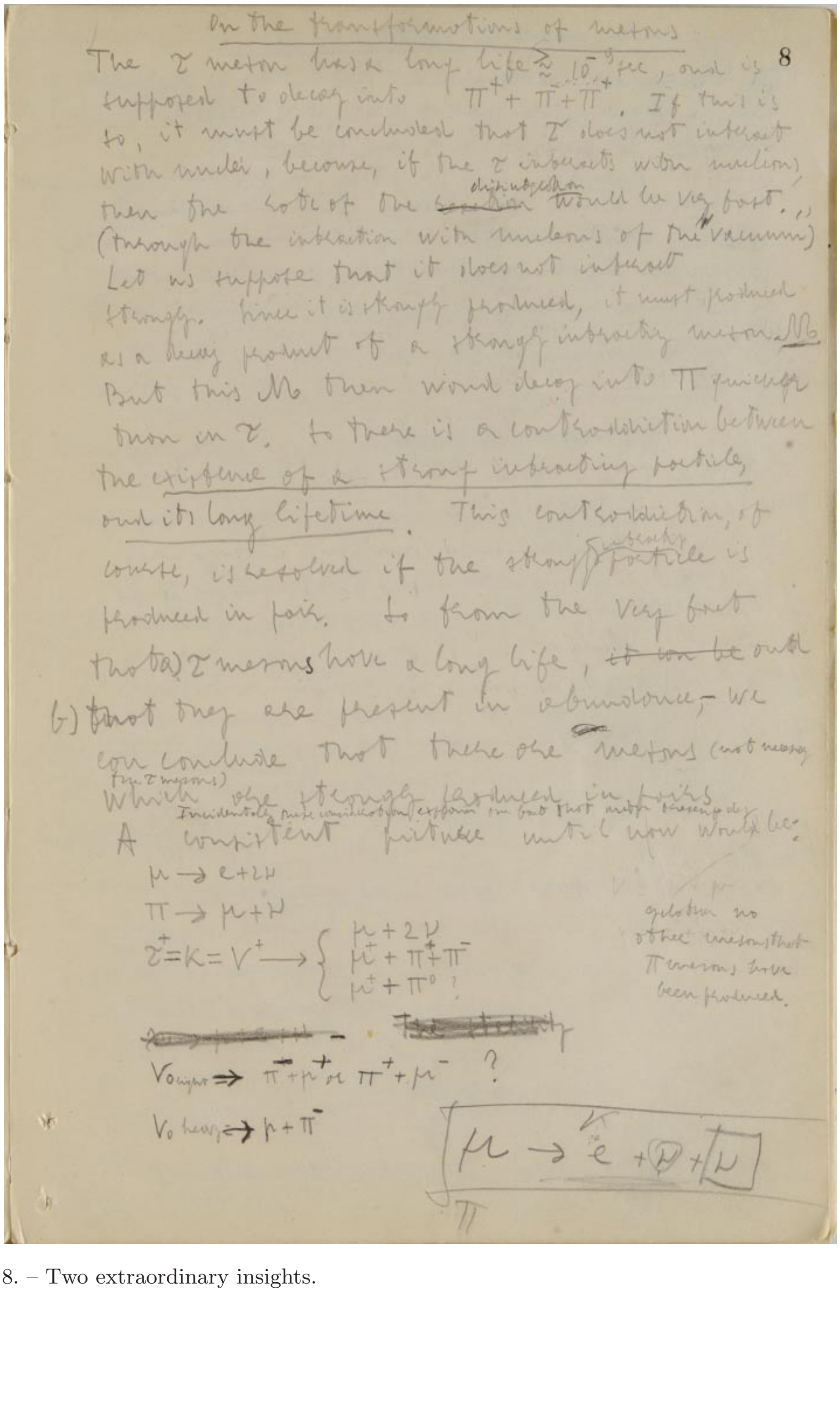
The definite evidence to support the theory of associated production comes from experiments at the Cosmotron of Brookhaven and at the Bevatron of Berkeley, thanks to their sufficiently high energy. Those results demonstrate that in the strong interaction the strangeness is conserved and that only the weak interaction can violate this quantum number in decays that are therefore with long lifetime.

The researches of Pontecorvo on the strange particles are never, or almost never, cited as one of the main contribution to the ideas that have led to the quark model and then to the Standard Model of Particle Physics. However, on page 8 of the logbook, there is the demonstration that Bruno already in 1950 had the intuition that the contradictory behavior of these strange particles can be explained by the hypothesis of production in pair. Unfortunately, this idea remained hidden in this notebook and in some internal reports written in Russian, not being accessible for a long time to the physics community outside the Soviet Union.

There is another very interesting element in the page 8 which allows us to suppose that, already in 1950, Pontecorvo suspects that the two neutrinos from the decay process $\mu \to e + 2\nu$ are particles of different nature. The note comes twelve years before the hypothesis is experimentally validated. Indeed, after writing that *"a consistent picture until now would be: $\mu \to e + 2\nu$"*, a few lines below, towards the end of the page, he rewrites the decay as $\mu \to e + \nu + \nu$ and he highlights the two neutrinos with different signs.

Eight years later, in 1958, at the Laboratory of Nuclear Problems in Dubna a high intensity 800 MeV proton cyclotron is planned to be built. It is a good opportunity for Pontecorvo to demonstrate that the two neutrinos from the muon decay are not the same particle. In the same way the anti-neutrino of the pion decay ($\pi^- \to \mu^- + \bar{\nu}_\mu$) differs in nature from the anti-neutrino of the β decay.

In the paper *"Electron Muon and Neutrino"* [10] he suggests a long list of reactions induced by neutrinos (or antineutrinos) that can not occur if the two neutrinos (or antineutrinos) are of different types, i.e. one associated to the electron (ν_e) and the other to the muon (ν_μ). With simple arguments of symmetry between charged leptons (electron and muon) and corresponding neutral leptons (neutrinos), Pontecorvo realizes that there must be two different types of the neutrinos: ν_e and ν_μ. *"There are no reasons for asserting that ν_e and ν_μ are identical particles"*, he writes in the article and then he continues with a series of considerations that favor the hypothesis of different types of neutrinos. In particular Pontecorvo suggests to use the new powerful accelerator, under


On the transformations of mesons

8

The τ meson has a long life ≳ 10^{-9} sec, and is supposed to decay into $\pi^{+} + \pi^{-} + \pi^{+}$. If this is so, it must be concluded that τ does not interact with nuclei, because, if the τ interacts with nucleons then the rate of the ~~reaction~~ disintegration would be very fast. (through the interaction with nucleons of the vacuum) Let us suppose that it does not interact strongly. Since it is strongly produced, it must produced as a decay product of a strongly interacting meson M. But this M then would decay into π quicker than in τ. So there is a contradiction between the existence of a strong interacting particle, and its long lifetime. This contradiction, of course, is resolved if the strong interacting particle is produced in pairs. So from the very fact that a) τ mesons have a long life, ~~it can be~~ and b) ~~that~~ they are present in abundance, — we can conclude that there are mesons (not necessary the τ mesons) which are strongly produced in pairs.

A consistent picture until now would be:

$\mu \rightarrow e + 2\nu$

$\pi \rightarrow \mu + \nu$

$\overset{+}{\tau} = K = V^{+} \longrightarrow \begin{cases} \mu + 2\nu \\ \mu^{+} + \pi^{+} + \pi^{-} \\ \mu^{+} + \pi^{0} \; ? \end{cases}$

$V_{0\,\text{light}} \Rightarrow \pi^{-} + \mu^{+}$ or $\pi^{+} + \mu^{-}$?

$V_{0\,\text{heavy}} \rightarrow p + \pi^{-}$

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

π

explain no other mesons that π mesons have been produced.

Fig. 8. – Two extraordinary insights.

design, to produce a $\bar{\nu}_\mu$ beam from pion decays. He wants to prove that the reaction $\bar{\nu}_\mu + p \to e^+ + p$ is forbidden, while the reaction $\bar{\nu}_\mu + p \to \mu^+ + n$ is possible. Unfortunately the 800 MeV cyclotron was never built in Dubna so Pontecorvo could never perform the experiment. Three years later a similar experiment was conducted at the Brookhaven AGS by G. Danby et al. [11] and it was experimentally demonstrated that $\nu_\mu \neq \nu_e$.

For this discovery L.M. Lederman, M. Schwartz and J. Steinberger were awarded the Nobel Prize in 1988.

The epitaph, $\nu_\mu \neq \nu_e$, engraved on the tombstone of Bruno Pontecorvo in the non-Catholic Cemetery in Rome is the recognition of the fact that he was the first to postulate the existence of a muon neutrino different from the electron neutrino and to propose an experiment to check it.

When Pontecorvo arrives in Russia, in 1950, he has already given a decisive contribution to the understanding of the particle named by Fermi "neutrino". In 1945, while working at the Chalk River Laboratory in Canada, he had proposed a remarkable method to detect neutrinos, which it was thought to be impossible at the time. In 1934, in fact, Bethe and Peierls [12] had estimated a very low probability of interaction between neutrinos and matter. Their calculation implied that a neutrino could penetrate 10^{16} km (corresponding to $\sim$1000 light years) of solid matter before interacting or, equivalently, that only one neutrino out of 10^{11} could interact in the travel through the whole Earth (they calculated a cross section of $\sigma < 10^{-44} cm^2$). In their paper they concluded that: *"It is therefore absolutely impossible to observe processes of this kind with neutrinos created in nuclear transformations"*.

For Pontecorvo this conclusion was too drastic. In the internal report of the Chalk River Laboratories entitled *"On a method for detecting free neutrinos"* [13] and dated 1945, Pontecorvo explains his absolutely brilliant idea on how its possible to capture a neutrino and prove its physical reality despite its trifling chance of interacting with anything. He writes: *"It has been currently stated in the literature that inverse β-processes produced by neutrinos can not be observed, due to the low yield. The object of this note is to show that experimental observation of neutrinos is not out of question and to suggest a method which might make an experimental observation feasible"*.

One year later, in a second report (*"Inverse β-process"* [14]), he proposes again to verify the existence of the neutrino through the so-called inverse beta decay process, i.e. the process in which a neutrino interacts with a neutron of a nucleus with charge Z. The neutron turns into a proton with emission of an electron, thus the nucleus becomes radioactive with charge Z+1. Pontecorvo himself asserts that this process is very rare and that *"it is true that the actual β transition involved, i.e. the actual emission of a β particle in process $\nu + Z \to \beta^- + (Z+1)$ is certainly not detectable in practice"*, but he adds: *"however, the nucleus of charge Z+1, which is produced in the reaction may be (and generally will be) radioactive with a decay period well known. The essential point, in this method, is that radioactive atoms produced by an inverse beta-ray process have different chemical properties from the irradiated atoms. Consequently it may be possible to concentrate the radioactive atoms from a very large irradiated volume."*
In the report, he suggests to use the reaction $\nu + Cl^{37} \to Ar^{37} + e^-$. He explains that, by irradiating a large amount of Chlorine with an intense source of neutrinos for a time of the order of one month, radioactive Argon-37 is produced. Through radiochemical methods, the unstable Argon-37 can be separated and the capture of an electron by Argon-37 that returns Chlorine-37 can be identified by detecting the 2.8 keV Auger electron emitted from the excited Chlorine-37 atom in the K-capture reaction.

Pontecorvo is clearly referring to this method when, at page 76 of the logbook, he

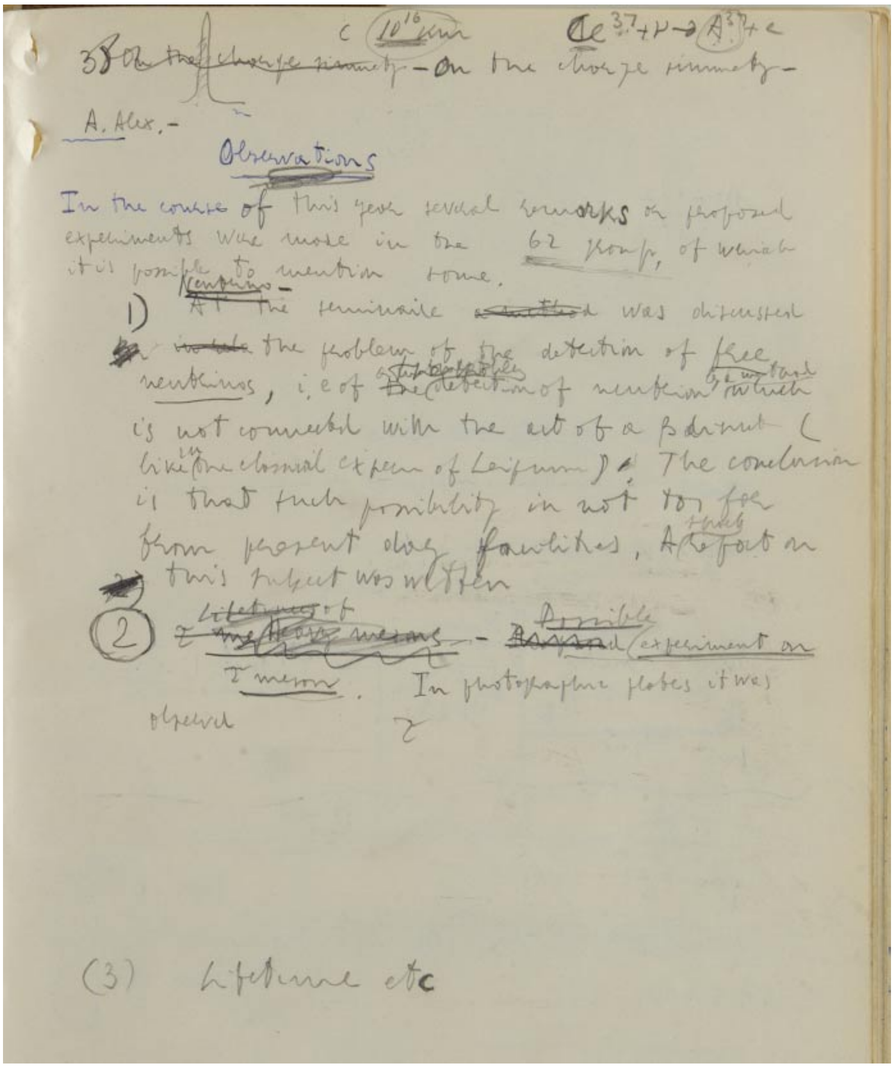


Fig. 9. – The Pontecorvo Chlorine-Argon method.

comments the activities that his group has carried out during 1951 (Figure 9).

In the top-right side of the page he writes the Chlorine-Argon reaction he has proposed in the Chalk River paper of 1946. Close to the formula he writes also the astronomical distance, according to the Bethe and Peierls calculation, the neutrinos can travel in matter before interacting, i.e. 10^{16} km. In writing this huge distance probably Pontecorvo is considering how large should be the amount of Chlorine required to detect such an elusive particle. In the page he remarks: *"At the seminaire was discussed the problem of the detection of free neutrinos, . . . The conclusion is that such possibility is not too far from present day facilities. A short report on this subject was written"*. From this note it is evident that Pontecorvo by the end of 1951 is almost sure to be able to detect free neutrinos. It should be really interesting to find the "short report" he refers, to understand how and where he thought to be possible performing this experiment in Russia.

Unfortunately, as remarked by the Russian physicist S.S. Gershtein, he could never realize his own brilliant ideas in the USSR because he had even denied access to any nuclear reactors which he considered to be the most promising source of neutrinos.

Three years later, in 1954, R. Davis tried to use this method for the first time by exposing a 3900 liters tank of Chlorine to the Brookhaven nuclear reactor and subsequently a 11,400 liters tank to the most powerful Savannah River reactor, without being able to produce the Chlorine-Argon reaction.
This was the first experimental indication that nuclear reactors are source of antineutrinos.

But Davis was not the only one who used a nuclear reactor as intense neutrino source, as proposed by Pontecorvo in his paper. One year before, in 1953, also F. Reines and C.L. Cowan Jr., have realized a 300 liters scintillation detector to capture neutrinos from the Hanford reactor with a detection technique different from that suggested by Pontecorvo. Only few years later, on June 14, 1956, with a different detector arrangement they announced in a telegram sent to Wolfgang Pauli in Zurich, to have unequivocally detected antineutrinos from the fission fragments of the Savannah River reactor.

For this discovery, in 1995, Reines was awarded the Nobel Prize in both of their names (Cowen was dead by that time).

In the famous Chalk River paper of 1946, Pontecorvo had proposed as neutrino source not only the "pile" but also the Sun. So, twenty years later, R. Davis developed an experiment based on the Pontecorvo Chlorine-Argon method, by placing a 378,000 liters tank of perchloroethylene, a commonly used dry-cleaning chemical, in the Homestake Gold Mine in South Dakota.
Davis' experiment confirmed that the sun produces neutrinos, but only about one-third of the number of neutrinos predicted by theory were detected. It is the so-called "solar neutrino deficit" predicted by Pontecorvo 10 years before, in the famous article *"Inverse beta processes and non-conservation of lepton charge"* [15]. In this paper Pontecorvo suggests his most remarkable and audacious idea, namely the *neutrino oscillations* and asserts that the phenomenon *"...will certainly occur, at least, on an astronomic scale"*.

In 2002 Davis was awarded the Nobel prize in Physics in particular "for the detection of cosmic neutrinos".

It is clear, from the annotations in the logbook, that Pontecorvo could have done these neutrino experiments already in 1951 if only he had the possibility to access facilities he believed already available in Russia. No doubt, that Pontecorvo for his brilliant ideas and insights could have been attributed more than one Nobel Prize. Of course, he was honoured the most prestigious awards of the Soviet Union: the Stalin Prize in 1954, the Lenin Prize in 1963 and many of the highest USSR orders. In 1964 he became a full member of the USSR Academy of Sciences.

Regretfully, the fact that in Soviet Union Pontecorvo could not access to nuclear reactors nor have available powerful particle accelerators —and maybe the necessary resources to build the experimental apparatus he had in mind— prevented him from realising his prophetic theoretical ideas and to perform those experiments that have brought, later, the Nobel Prize to many other scientists.

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