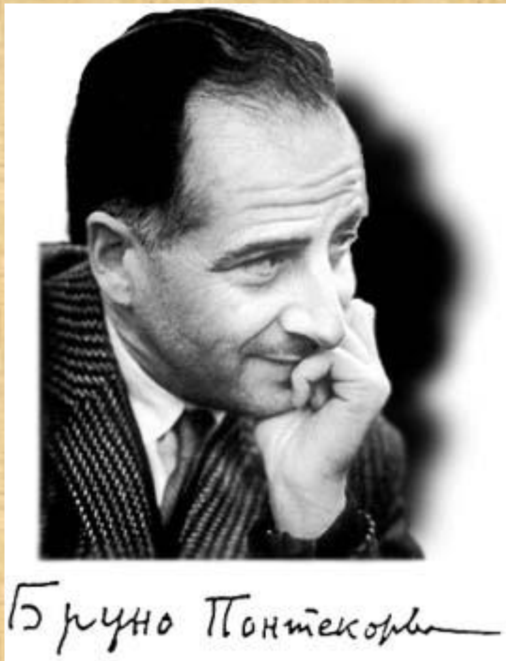
The early years of Bruno Maximovich Pontecorvo at Dubna



It is really a pleasure and a great honor for me to present some of the activities of Bruno Maximovich Pontecorvo at the Institute of Nuclear Problems of Dubna.
I will mainly focus on the early years of his activity at Dubna, since other Speakers at this Symposium will certainly present his full activity in a much better way than I could do.

Rino Castaldi
INFN-Pisa

Let me try to imagine Bruno Pontecorvo as man and scientist when, in September 1950 at the age of 37 year old, he decided to move with his family to Moscow.

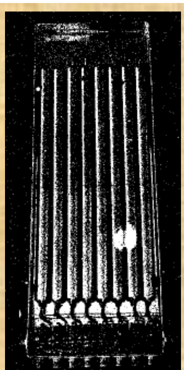
An experimental physicist expert on advanced detector techniques

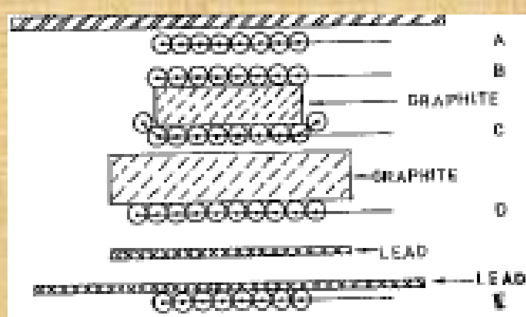
He has just published a review (*"Recent development in proportional counter technique, Helv. Phys. Acta, 1950, vol 23, Suppl. 3, p.97-118)* based on his work on high multiplication proportional counters, done al Chalk River Laboratory which allow to detect not only the position of a charged particle but also the ionization energy released by the particle even in presence of small ionization.

The gas detectors he describes in this paper, except from the readout electronics, are not much different from the wire gas chambers of nowadays:

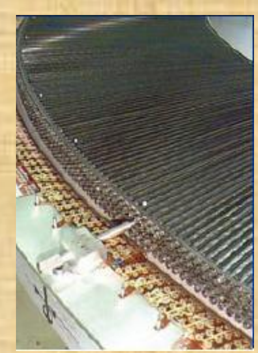
- tungsten wires of 50-100 μm in diameter
- cathode tubes up to 50 cm long and ranging from 0.2 to 5 cm in diameter
- filled with Ar (or Xe) + 20% CH_4 as gas quencher
- applied voltages of 2-3 KV….

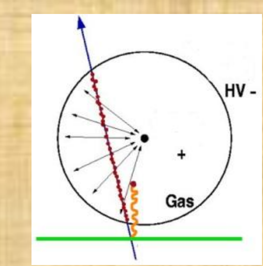
Not too much different from the 4 mm straw tubes of the TRT of ATLAS !!!

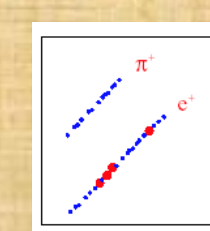




Proportional gas tubes used by Pontecorvo







Proportional gas straw tubes used by ATLAS

A theoretical physicist with a prophetic vision of weak interaction

After the famous experiment of Conversi, Pancini and Piccioni and the interpretation given by Fermi,Teller and Weisskopf that the mesotron measured in cosmic rays is not the strong interacting particle foreseen by Yukawa theory, Pontecorvo immediately published the paper *"Nuclear capture of mesons and the meson decay"* *(Phys. Rev.,1947,72,p.246)* where he writes:

"We notice that the probability (~$10^{-6}sec^{-1}$) of capture of a bound negative mesons is of the order of the probability of ordinary K-capture process, when allowance is made for different in the disintegration energy and the difference in the volumes of the K-shell and of the meson orbit."

And immediately concludes:

"We assume that this is significant and wish to discuss the possibility of a fundamental analogy between β-processes and processes of emission or absorption of charged mesons."

Pontecorvo first had the intuition of the *e-μ* universality of weak interaction !

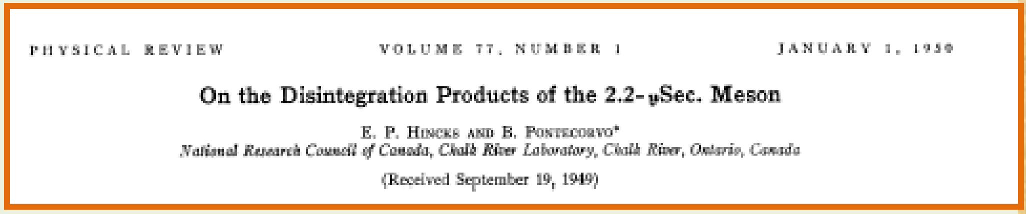
In one of his recollection *"The infancy and youth of neutrino physics"* *(Journal de Physique,1982,12,vol.43,p.C8-221)* he writes **"…I became fascinated by the particle which we call now the muon"**. He immediately started, in collaboration with T. Hincks, to prepare some experiments with cosmic rays to study the properties of the muon decay. He was eager to answer questions like: does the muon decay in an electron and one or two neutrinos ? does it decay in an electron and a photon? Are particles other than electrons and neutrinos emitted in muon decay?

A good tennis player catching the e-μ universality by Misha Bilenky

A theoretical and an experimental physicist

Pontecorvo, as experimental physicist decides to answer the questions that the Pontecorvo theoretical physicist asks to himself.

A series of experiment performed in collaboration with E. P. Hincks gives him the answers he is looking for:


PHYSICAL REVIEW VOLUME 77, NUMBER 1 JANUARY 1, 1950

On the Disintegration Products of the 2.2-μSec. Meson

E. P. Hincks and B. Pontecorvo*
National Research Council of Canada, Chalk River Laboratory, Chalk River, Ontario, Canada

(Received September 19, 1949)

- *in the muon decay the charged particle is an electron*
- *the decay process is kinematically consistent with a decay to one electron + two neutrinos*
- *no high energy photon is emitted in the 2.2 μsec decay*

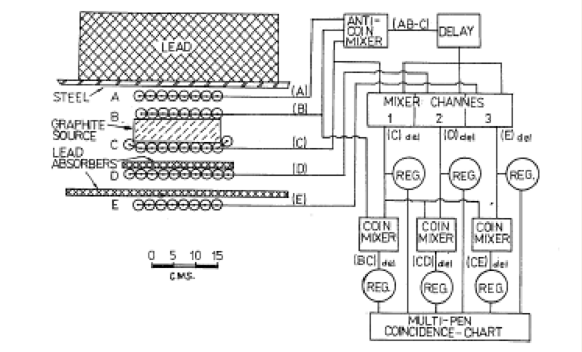
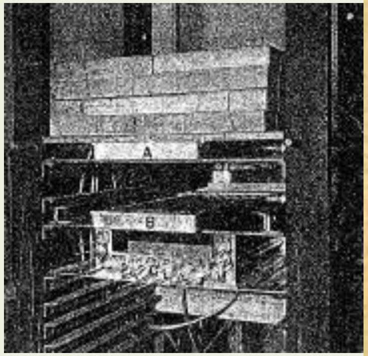


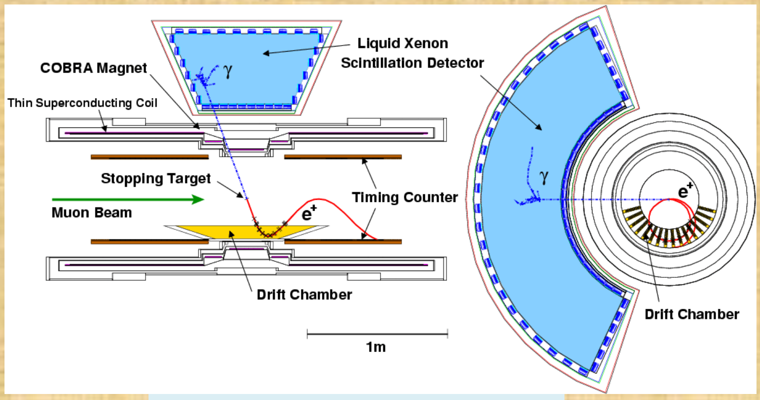
Fig.8. Experimental arrangement for the detection of bremsstrahlung, with simplified block diagram of the circuits. The lengths of the counters and source are ~40 cm



65 years later the MEG experiment is still looking for the $\mu \rightarrow e+\gamma$ decay

BR($\mu \rightarrow e+\gamma$) < 5.7 x 10^{-13} (90% C.L.)

(muon beam: 3 x 10^7 μ/s)



MEG Experiment

A person who strongly believes in the Communism

Bruno Pontecorvo is a deeply convinced communist who believes in a true socialist society inspired by a profound sense of justice and equality.

"Le mie opinioni politiche sono di sinistra. In origine esse erano dovute soprattutto al mio odio per il fascismo e, io penso ora, al senso di giustizia inculcatomi da mio padre....., opinioni dominate da una categoria non logica che io chiamo adesso "religione", una specie di "credo fanatico"....."

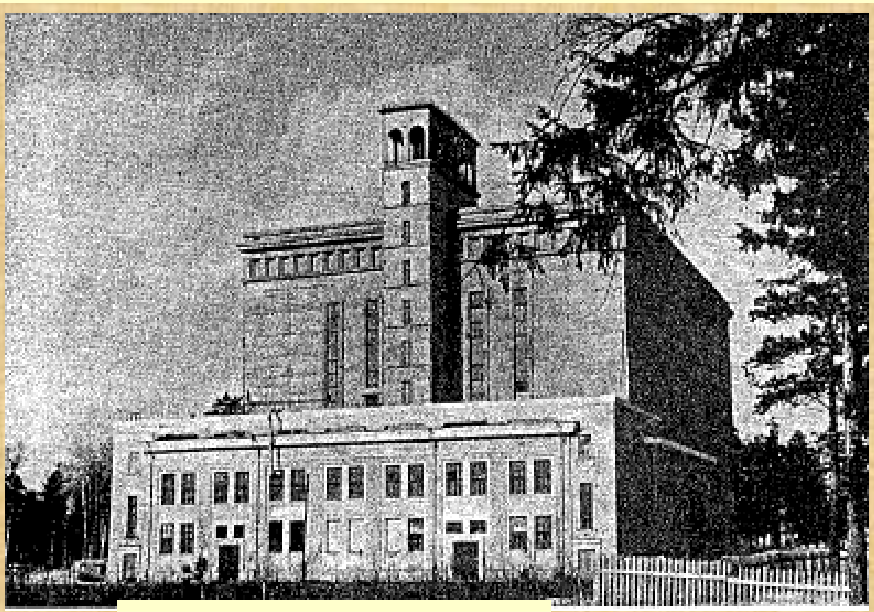
(My political views are leftist. Originally, they were mainly due to my hate against the fascism and, I think now, the sense of justice instilled in me by my father. . ., political views dominated by a not logical category that now I call "religione", a kind of "fanatical belief"...)

He writes these sentences in an autobiographic note of 1988/89 for the "Enciclopedia della Scienza e della Tecnica" (Arnoldo Mondadori Editore).
When he writes this note he is still convinced that with the "Perestroika" of Mikhail Gorbachev the Soviet Union will become a true democratic socialist society funded on advanced laws and on human rights *"fondata su leggi avanzate e sui diritti dell'uomo".*

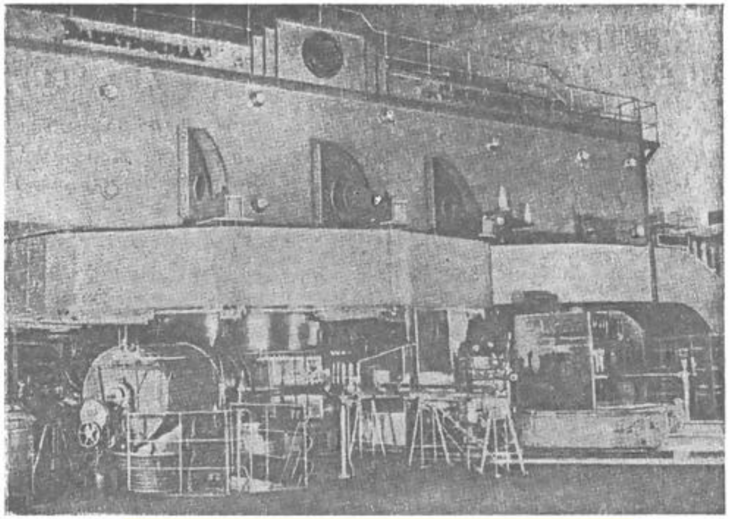
I have a profound respect and admiration for this man who strongly believed that such hypothetical society is not an utopia and devoted all his life in trying to realize it.

New life and new experiments in Dubna

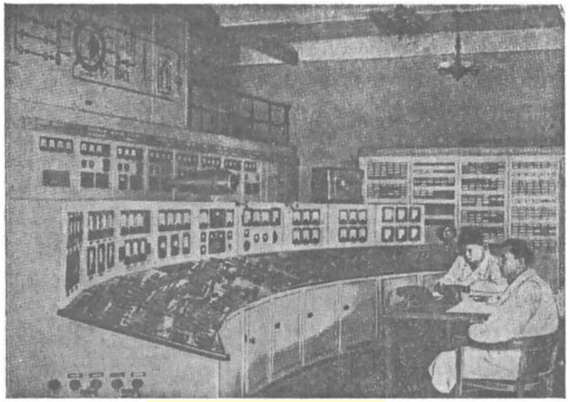
Certainly Bruno Pontecorvo must have been enthusiastic to arrive to the Institute of Nuclear Problems beginning of November 1950, and to have the possibility to work at the five-meter synchrocyclotron, the most powerful existing at that time in the world.



Synchrocyclotron building



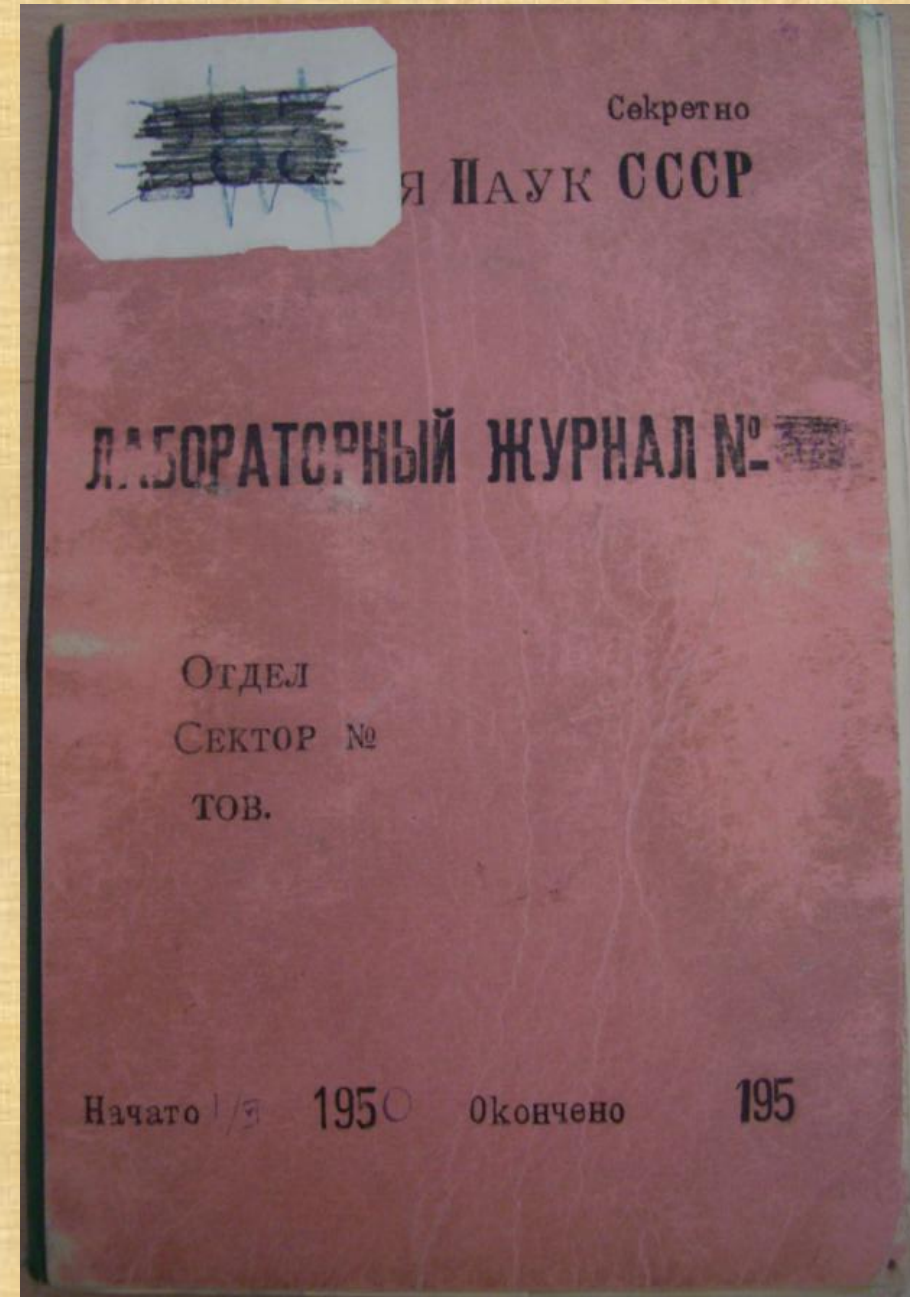
Synchrocyclotron general view



Control room

	Kind of accelerated particles and their energy		
	280 MeV deuterons	560 MeV α's	480 MeV protons
Internal target current (μA)	1	0,025	0,2—0,3
Extracted proton flux at a distance of 10 m from the magnetic channel ($cm^{-2} sec^{-1}$)	—	—	$1 \cdot 10^4$ (E_p = 460 MeV)
Neutron flux at the maximum of the angular distribution 2 m from the internal target ($cm^{-2} sec^{-1}$)	$8 \cdot 10^7$	$2 \cdot 10^5$	$5 \cdot 10^6$
Neutron energy at the maximum of the energy distribution (MeV)	120	120	380
Halfwidth of the angular neutron distribution (radian)	0,17	0,35	0,55
Process responsible for neutron production	Stripping	α-particle disintegration	charge exchange

Parameters of available beams in 1950



1st November 1950

Pontecorvo begins his research work with the Synchrocyclotron of the Institute of Nuclear Problems in Dubna.

Here we have his first Logbook/Notebook where Pontecorvo books his everyday thoughts, ideas, projects, drafts, and data taking, etc. during the first period of his stay in Dubna.

Thanks to Gloria Spandre and Elena Volterrani who got this precious document from Gil Pontecorvo, the son of Bruno.

Page 1 of the notebook

1st November (1950)

- <u>Neutron production by cyclotron particles</u> -

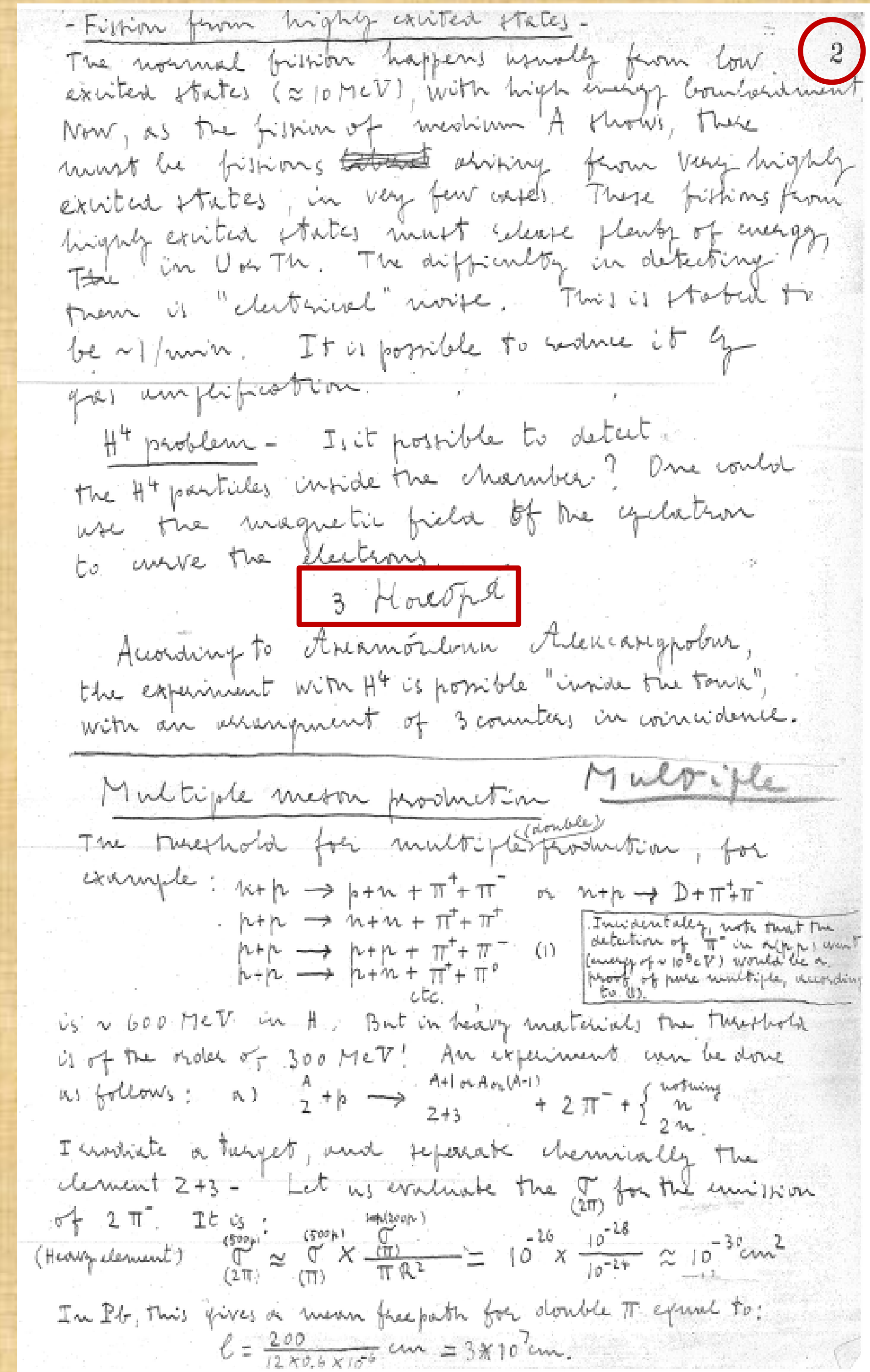
1° Novembre

- 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 ~~[illegible]~~ ~~[illegible]~~ relaxation lenght would be probably characteristic of the " ~~[illegible]~~ knock on" process.

"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 $r^2|_{Av.}$)."

(At the end of 1950 the neutrons are produced with the 560 MeV α-particles beam of the cyclotron colliding on internal targets of various substances and the energy is not very well known.)



2

- Fission from highly excited states -

The normal fission happens usually from low excited states (≈ 10 MeV), with high energy bombardment. Now, as the fission of medium A shows, there must be fissions ~~[illegible]~~ arising from very highly excited states, in very few cases. These fissions from highly excited states must release plenty of energy. ~~The~~ in U or Th. The difficulty in detecting them is "electrical" noise. This is stated to be ~1/min. It is possible to reduce it by gas amplification.

H^4 problem - Is it possible to detect the H^4 particles inside the chamber? One could use the magnetic field of the cyclotron to curve the electrons.

3 Ноября

According to Анатолий Александрович, the experiment with H^4 is possible "inside the tank", with an arrangement of 3 counters in coincidence.

Multiple meson production   Multiple

The threshold for multiple (double) production, for example:

$n+p \to p+n+\pi^+ +\pi^-$ or $n+p \to D+\pi^+ +\pi^-$

$p+p \to n+n+\pi^+ +\pi^+$

$p+p \to p+p+\pi^+ +\pi^-$ (1)

$p+p \to p+n+\pi^+ +\pi^0$

etc.

Incidentally, note that the detection of π^- in p,p (want energy of ~ 10^9 eV) would be a proof of pure multiple, according to (1).

is ~ 600 MeV in H. But in heavy materials the threshold is of the order of 300 MeV! An experiment can be done as follows: a) $^{A}_{Z} + p \to {}^{A+1 \text{ or } A \text{ or } (A-1)}_{Z+3} + 2\pi^- + \{\text{nothing}, n, 2n\}$

Irradiate a target, and separate chemically the element Z+3. Let us evaluate the $\sigma_{(2\pi)}$ for the emission of $2\pi^-$. It is:

(Heavy element) $\sigma^{(500)}_{(2\pi)} \approx \sigma^{(500)}_{(\pi)} \times \frac{\sigma^{(300)}_{(\pi)}}{\pi R^2} = 10^{-26} \times \frac{10^{-28}}{10^{-24}} \approx 10^{-30}\ cm^2$

In Pb, this gives a mean free path for double π equal to:

$l = \frac{200}{12 \times 0.6 \times 10^{-6}}\ cm = 3 \times 10^7\ cm.$

Page 2: 3^{th} November (1950)

Pontecorvo writes in this book some thoughts on which kind of experiments with what techniques can be done using the available cyclotron beams:

- *Fission from highly excited states* -

……..The difficulty in detecting them is "electrical" noise. This is stated to be ~1/min. It is possible to reduce it by gas amplification

H^4 problem – *Is it possible to detect the H^4 particles inside the chamber ? One could use the magnetic field of the cyclotron to curve the electrons.*

3^{th} November

According to Anatoly Alexandrovich, the experiment with H^4 is possible "inside the tank", with an arrangement of 3 counters in coincidence.

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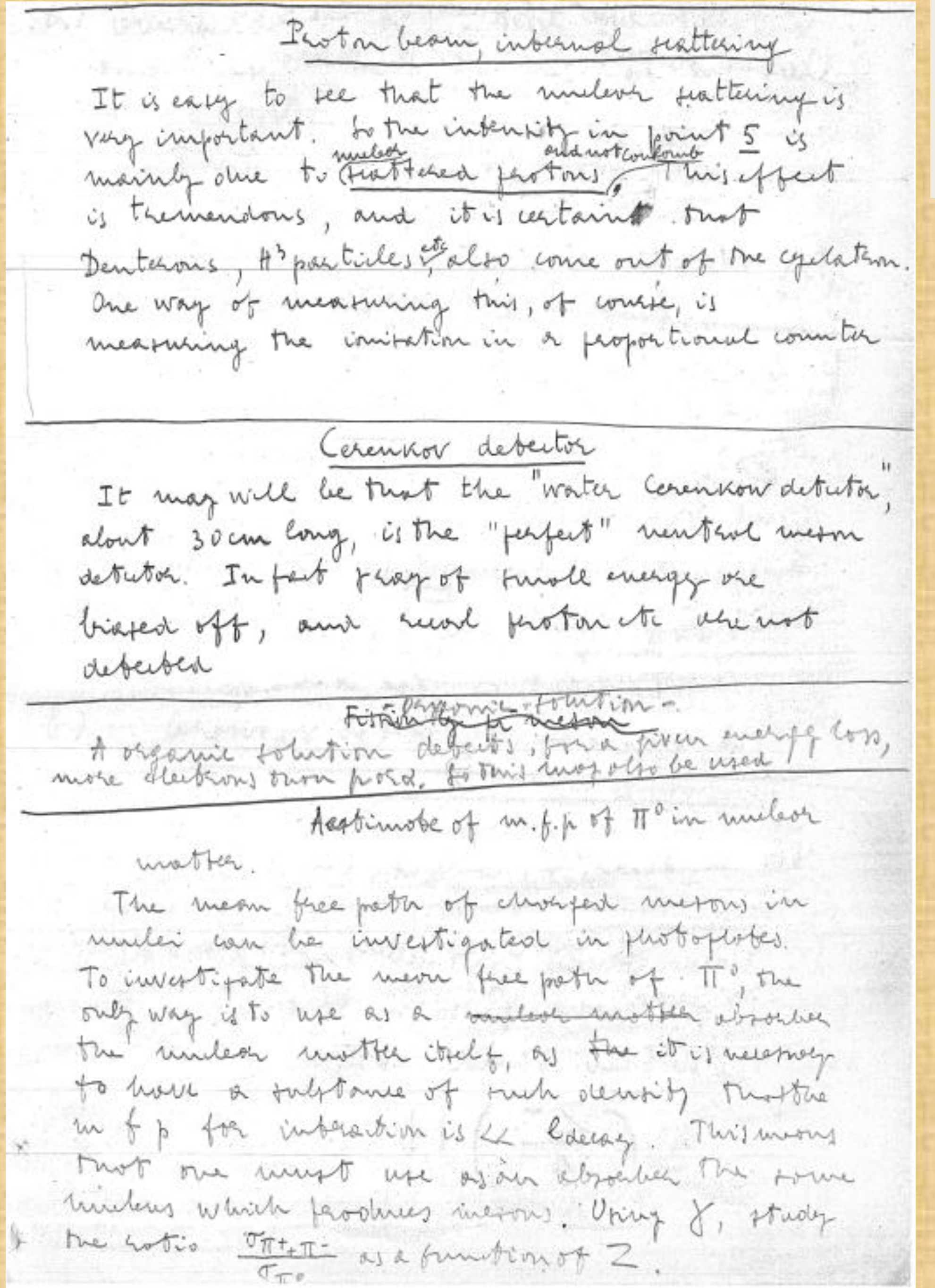

Proton beam, internal scattering

It is easy to see that the nuclear scattering is very important. So the intensity in point 5 is mainly due to nuclear scattered protons (and not coulomb). This effect is tremendous, and it is certain that Deuterons, H^3 particles etc, also come out of the cyclotron. One way of measuring this, of course, is measuring the ionization in a proportional counter

Cerenkov detector

It may well be that the "water Cerenkov detector", about 30 cm long, is the "perfect" neutral meson detector. In fact γ ray of small energy are biased off, and recoil proton etc are not detected

~~Fotomultiplier for mesons~~ Organic solution –

A organic solution detects, for a given energy loss, more electrons than for α, so this may also be used

A estimate of m.f.p of π^0 in nuclear matter.

The mean free path of charged mesons in nuclei can be investigated in photoplates. To investigate the mean free path of π^0, the only way is to use as a ~~nuclear matter~~ absorber the nuclear matter itself, as ~~the~~ it is necessary to have a substance of such density that the m f p for interaction is $\ll l_{decay}$. This means that one must use as an absorber the same nucleus which produces mesons. Using γ, study the ratio $\frac{\sigma_{\pi^+ + \pi^-}}{\sigma_{\pi^0}}$ as a function of Z.

Pontecorvo continues writing, up to page 9, some thoughts on which kind of experiments with what techniques can be done using the available cyclotron beams:

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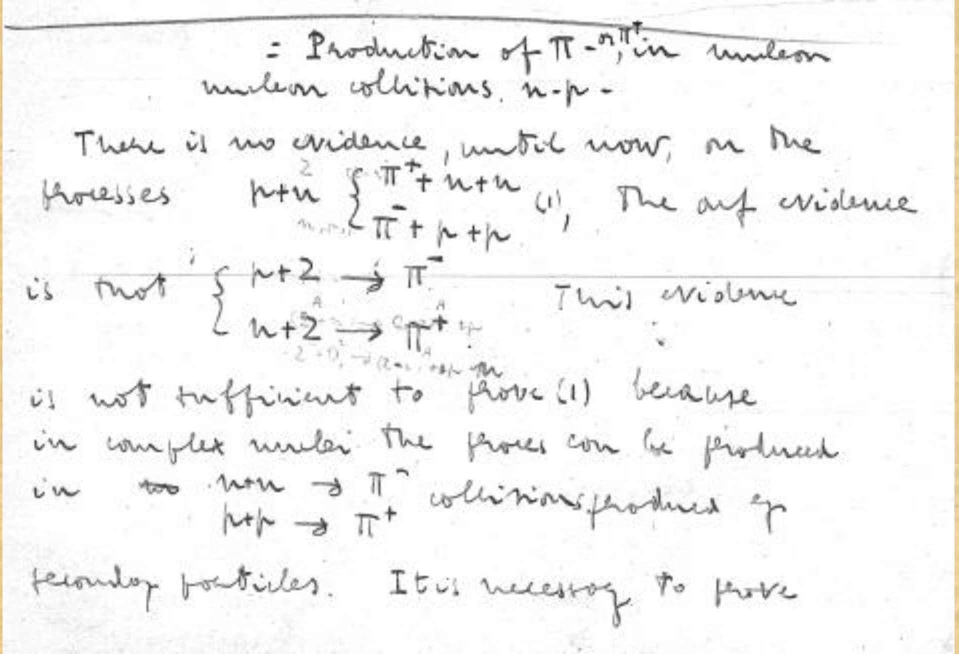
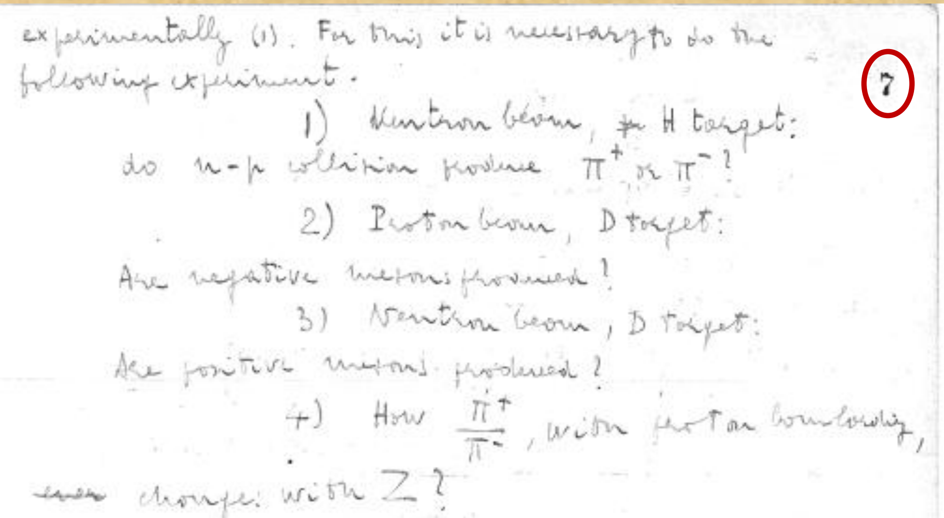
He continues writing up to page 9 of his notebook some thoughts on which kind of experiments with what techniques can be done using the available cyclotron beams





= *Production of π^- or π^+, in nucleon nucleon collisions* n-p -

There is no evidence, until now, on the processes

$$p+n \begin{cases} \pi^+ + n + n \\ \pi^- + p + p \end{cases} \quad (1),$$

the only evidence is that

$$\begin{cases} p+Z \rightarrow \pi^- \\ n+Z \rightarrow \pi^+ \end{cases}$$

This evidence *is not sufficient to prove* (1) *because in complex nuclei the process can be produced in*

$$\begin{matrix} n+n \rightarrow \pi^- \\ p+p \rightarrow \pi^+ \end{matrix}$$

collisions produced by secondary particles. It is necessary to prove experimentally (1). *For this is necessary to do the following experiment.*

1) *Neutron beam,* H *target* : *do n-p collisions produce π^+ or π^-?*
2) *Proton beam,* D *target* : *Are negative mesons produced?*
3) *Neutron beam,* D *target* : *Are positive mesons produced?*
4) *How π^+ / π^-, with proton bombarding, changes with Z?*

Very interesting what he writes on page 8! !

(beginning of November 1950)

On the transformations of mesons -

The τ meson has a long life $>\approx 10^{-9}$ 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 disintegration would be very fast.
(trough the interaction with nucleons of the vacuum)
*Let us suppose that it does not interact strongly . Since 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 his long lifetime. This contradiction, **of course** , is resolved if the strongly interacting particle **is produced in pair**.*(*) *So from the very fact that a) τ mesons have a long life, b) that they are present in abundance, - we can conclude that there are mesons (not necessarily the τ mesons) which are strongly produced in pairs.*
(incidentally these considerations explain the fact that until present day cyclotron no other mesons that π mesons have been produced.)
A consistent picture until now would be:

$$\mu \rightarrow e+2\nu$$

$$\pi \rightarrow \mu+\nu$$

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

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

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

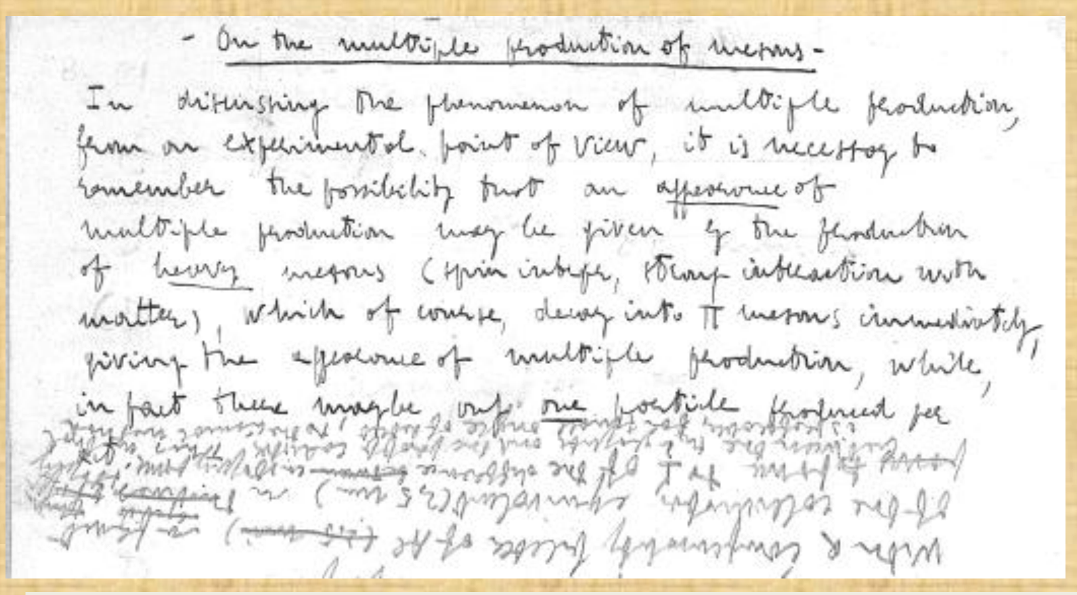
$$\overset{K}{\mu \rightarrow e + \textcircled{\nu} + \boxed{\nu}} \quad (**)$$

π

(*) here, at the end of 1950, **without the notion of strangeness**, a deep intuition is needed **to propose a production process in pair** to solve this contradiction.
(**)maybe just a coincidence! Two lines before he writes $\mu \rightarrow e+2\nu$ while here he writes $\mu \rightarrow e+\nu+\nu$ engraving the neutrinos with two different signs.

Two profound intuitions in a single page ?!

On page 9 he writes only the following few lines "On the multiple production of mesons", while the remaining part of the page, written in a reversed order, is the end of the draft of a paper.

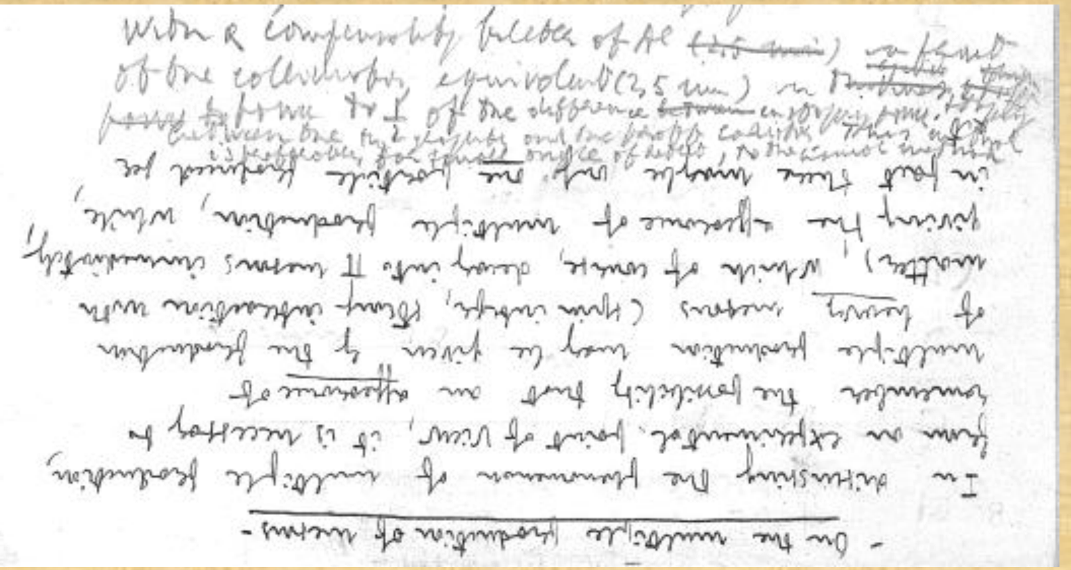


-*On the multiple production of mesons* –

In discussing the phenomenon of multiple production, from an experimental point of view, it is necessary to remember the possibility that an appearance of multiple production may be given by the production of heavy mesons (spin integer, strong interaction with matter), which of course decay into π mesons immediately, giving the appearance of multiple production, while, in fact there maybe only one particle produced per hit.

…. with a compensating filter of Al ~~(2.5cm)~~ in front of the collimator, equivalent (2.5cm) in… This method is preferable for small angle of detect(ion) to the ……(?) method.

Apparently Pontecorvo, after the first 9 pages, stops writing on this Notebook and he resumes writing only the following year (September 14th, 1951, see next slide) turning the book on the opposite side, starting from the last page and writing in the Notebook until March ≥ 24th, 1952.



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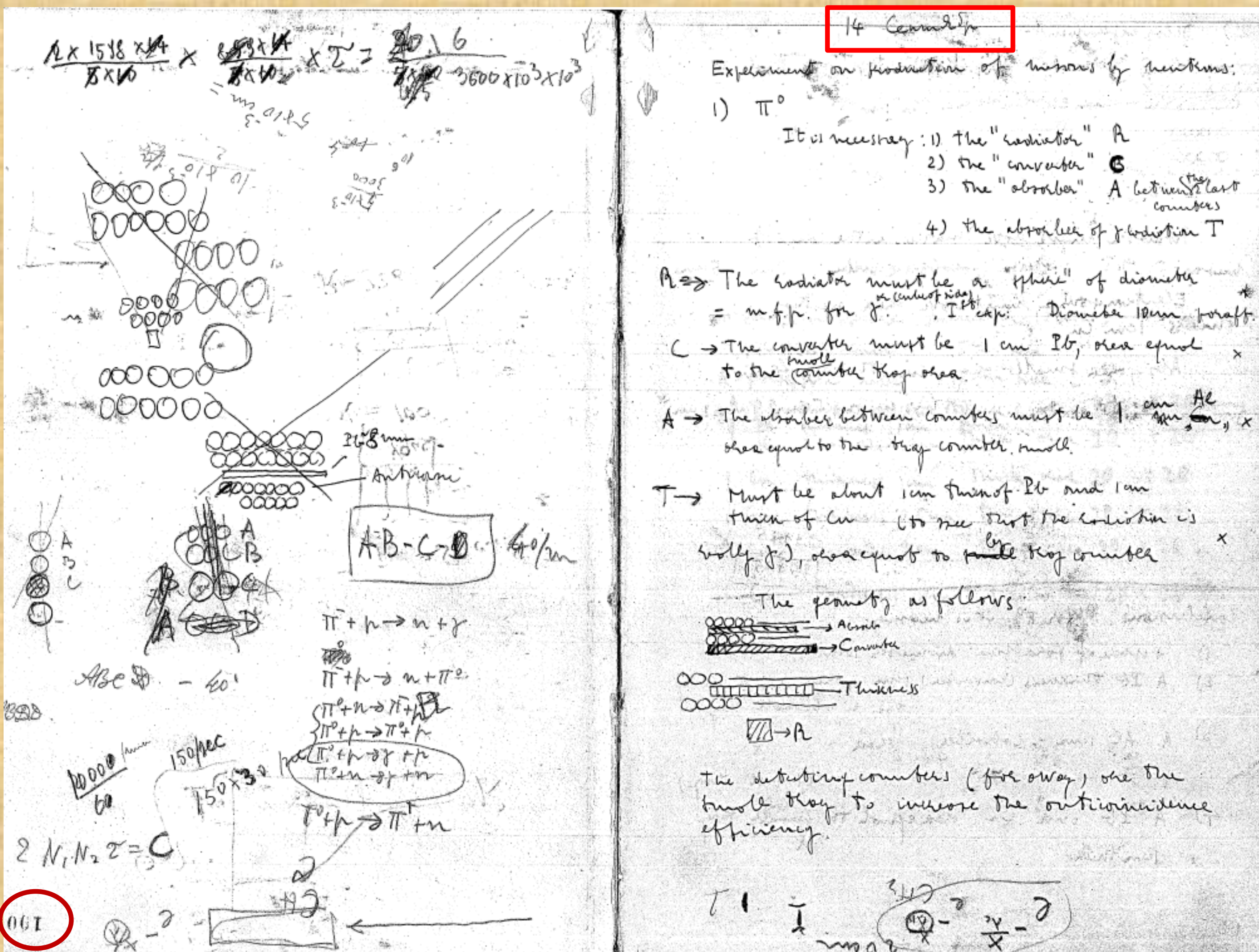
Pontecorvo resumes writing on the Notebook the following year, September 14, 1951, starting from the last page (n.100) turning the book on the opposite side.

He has now decided what to do and he is ready to make an "Experiment on production of mesons by neutrons":



14 September

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 2 last counters*
4) *the absorber of* γ *radiation* **T**

R → *The radiator must be a "sphere" ....*
....

C → *The converter must be 1 cm Pb,....*
....

A→ *The absorber between counters ....*
....

T→ *Must be about 1 cm thin of Pb,....*
....

The geometry as follows:
....
....

And he continues writing what we could call today the *"Technical Proposal"* of the experiment...

In September 1951, less than one year after his arrival in Dubna, Bruno Maximovich Pontecorvo is a respected group leader of a group of young physicists (Vladimir, Anatol, Alex, Adolph and George Selivanov). In group meetings he assigns the work to be done by each member, defines the program to be fulfilled, etc. as for instance is done in these three pages:

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

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

Have β counters ready.

Have α counter ready

3) George

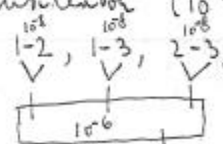
1) Finish work on duty factor + report.

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 ~~unit~~ 3 channel coincidence contact canister of 8 liquids + scintillator (10^{-8} sec), on the principle of

1-2, 1-3, 2-3 double coincidence 10^{-8}, triple 10^{-6} + 1 channel coincid. or anti, external



external, coincid, 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

Program

1) Measure the effective duty factor of the cyclotron as follows - For this:

a) Measure the resolving time of the system (using continuous sources).

b) Measure the accidental rates when the cyclotron works.

Experiment a: In the cyclotron building with a distance of two trays of CD about 10 m, and with 2 sources, measure:

1) Single rates, and coincidence: CD-A-B, from this we get 2τ. ~~some without~~

2) Some with no source for correcting values in subsequent experiment.

Experiment b:

1) When cyclotron works, single rates and coincidence rates.

Measurement of α, duty factor.

I) Take 2 single counters, +

II) Put them on the beam, far away from each other, and measure A B (AB)

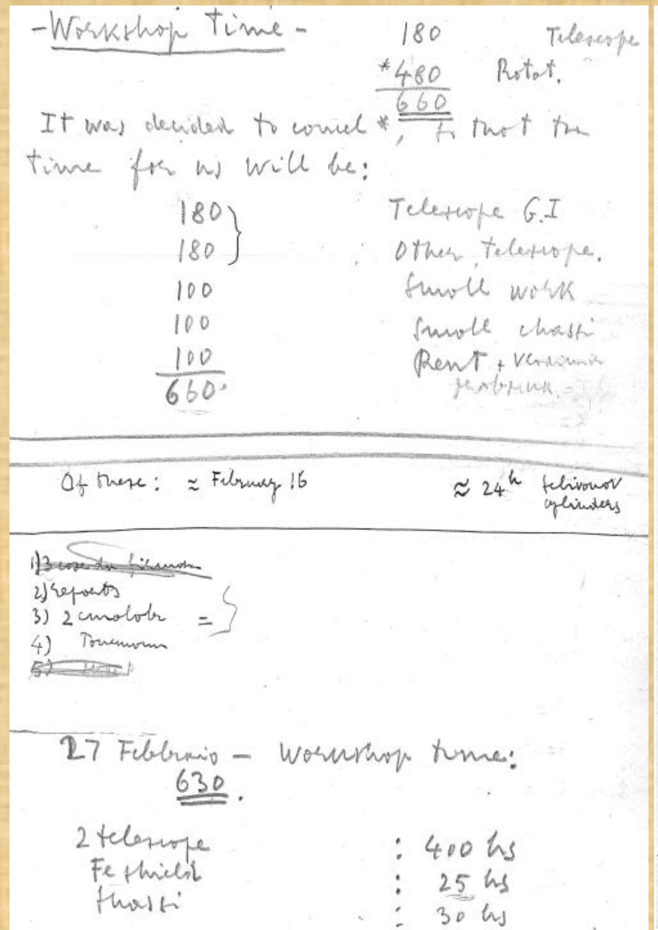
III) ~~Verify that~~ Verify that the cyclotron is constant.

IV) ~~For various condition of~~ Measure also after shutdown, A, B (AB).

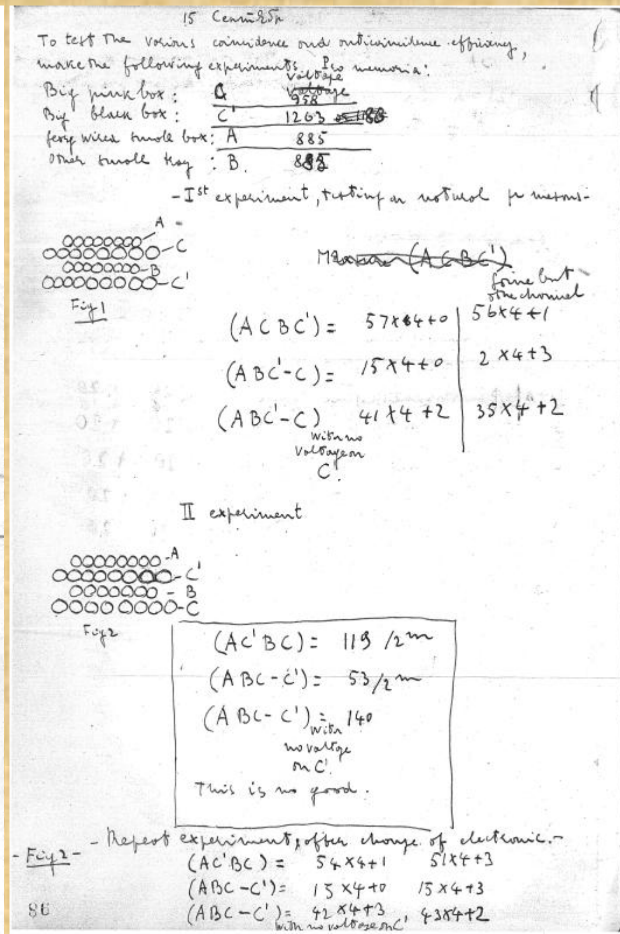
V) Write all data relative to the cyclotron

VI) If the experiments are reasonably reproducible, try various conditions of cyclotron.

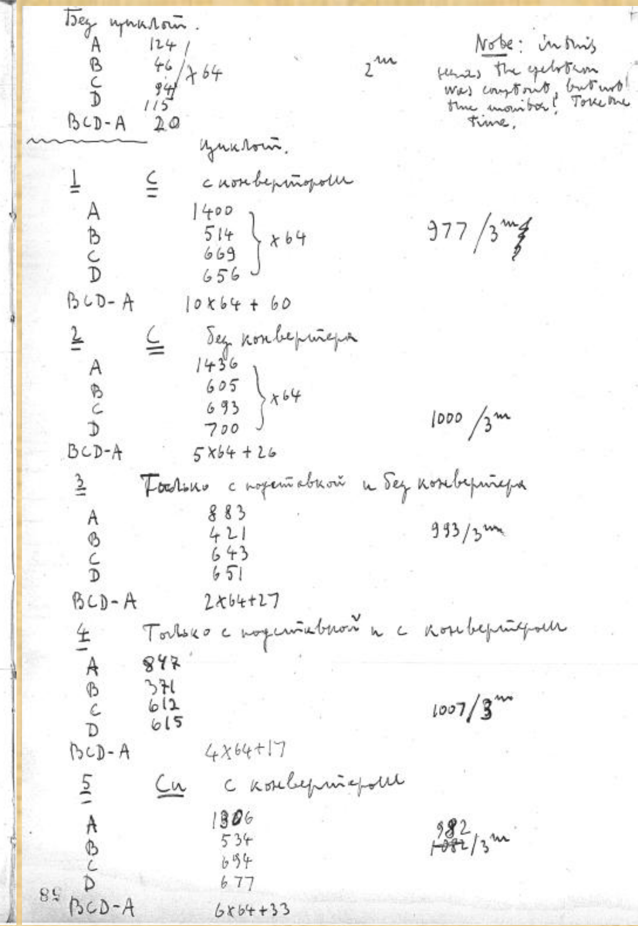
The activity of the group is rather well documented daily



Workshop time requested and used to build support and mechanical structures

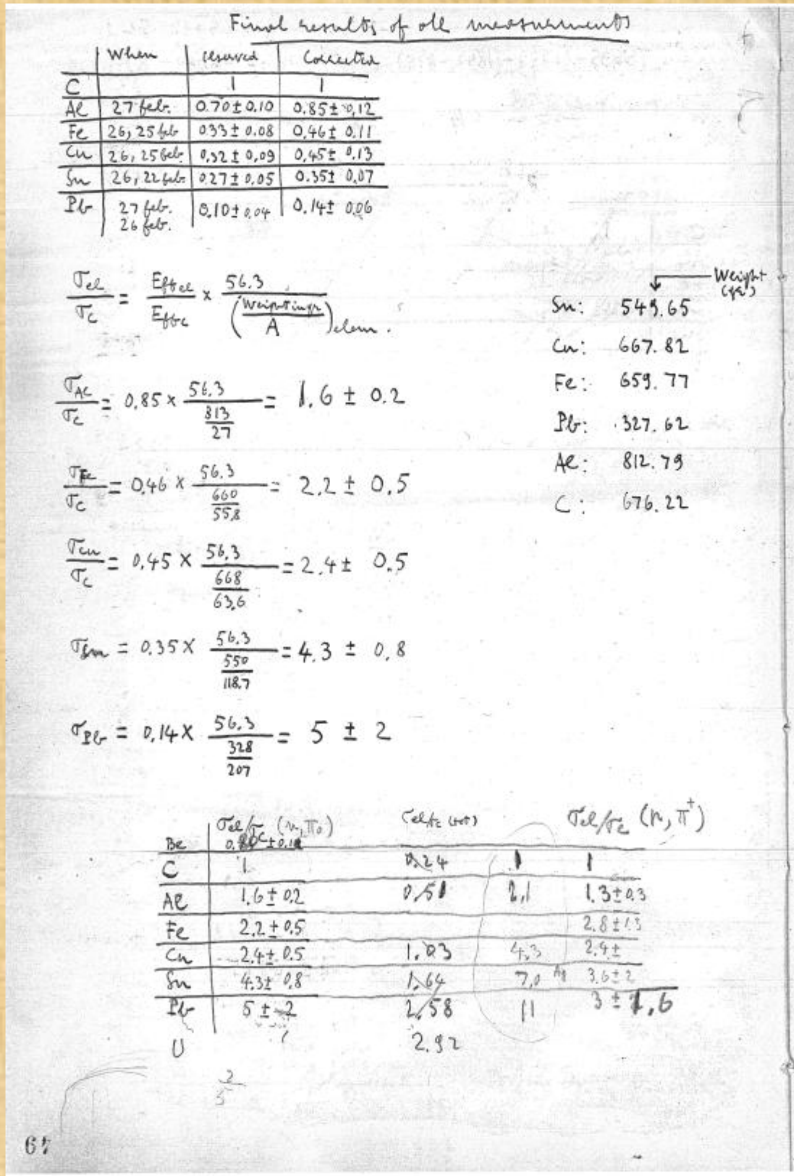


Measurements to test the various coincidence and anticoincidence efficiencies



Data taking

The activity of the group is rather well daily documented



Final results of all measurements

	When	Observed	Corrected
C		1	1
Al	27 feb.	0.70 ± 0.10	0.85 ± 0.12
Fe	26, 25 feb	0.33 ± 0.08	0.46 ± 0.11
Cu	26, 25 feb	0.32 ± 0.09	0.45 ± 0.13
Sn	26, 22 feb	0.27 ± 0.05	0.35 ± 0.07
Pb	27 feb. 26 feb.	0.10 ± 0.04	0.14 ± 0.06

$$\frac{\sigma_{el}}{\sigma_C} = \frac{Eff_{el}}{Eff_C} \times \frac{56.3}{\left(\frac{Weight\ in\ gr}{A}\right)_{elem.}}$$

Weight (gr):

Sn: 549.65

Cu: 667.82

Fe: 659.77

Pb: 327.62

Al: 812.79

C: 676.22

$$\frac{\sigma_{Al}}{\sigma_C} = 0.85 \times \frac{56.3}{\frac{813}{27}} = 1.6 \pm 0.2$$

$$\frac{\sigma_{Fe}}{\sigma_C} = 0.46 \times \frac{56.3}{\frac{660}{55.8}} = 2.2 \pm 0.5$$

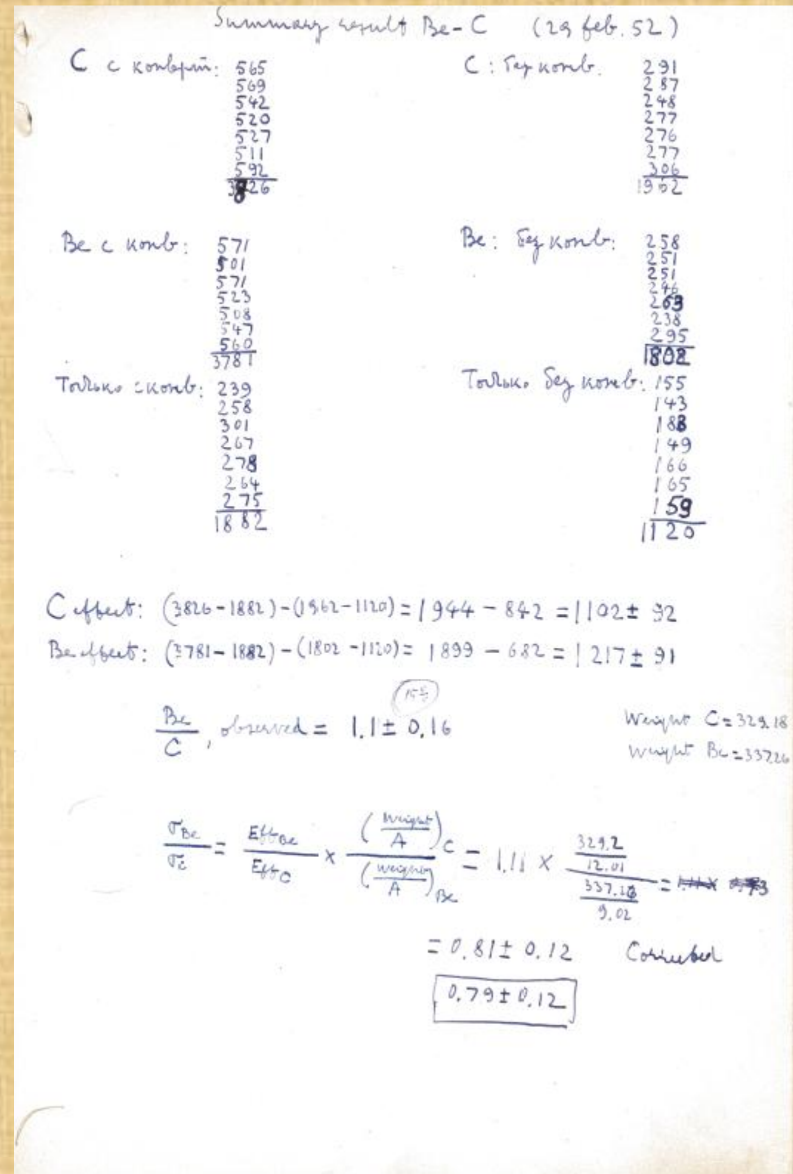
$$\frac{\sigma_{Cu}}{\sigma_C} = 0.45 \times \frac{56.3}{\frac{668}{63.6}} = 2.4 \pm 0.5$$

$$\sigma_{Sn} = 0.35 \times \frac{56.3}{\frac{550}{118.7}} = 4.3 \pm 0.8$$

$$\sigma_{Pb} = 0.14 \times \frac{56.3}{\frac{328}{207}} = 5 \pm 2$$

	σ_{el}/σ_C (n,π^0)	σ_{el}/σ_C		σ_{el}/σ_C (n,π^+)
Be	0.81 ± 0.12			
C	1	0.24	1	1
Al	1.6 ± 0.2	0.51	2.1	1.3 ± 0.3
Fe	2.2 ± 0.5			2.8 ± 1.3
Cu	2.4 ± 0.5	1.03	4.3	2.4 ±
Sn	4.3 ± 0.8	1.64	7.0	3.6 ± 2
Pb	5 ± 2	2.58	11	3 ± 1.6
U		2.92		

67



Summary result Be-C (29 feb. 52)

C с комбин.: 565, 569, 542, 520, 527, 511, 592 — 3826

C: без комб.: 291, 287, 248, 277, 276, 277, 306 — 1962

Be с комб.: 571, 501, 571, 523, 508, 547, 560 — 3781

Be: без комб.: 258, 251, 251, 246, 263, 238, 295 — 1802

Только с комб.: 239, 258, 301, 267, 278, 264, 275 — 1882

Только без комб.: 155, 143, 188, 149, 166, 165, 159 — 1120

C effect: (3826 − 1882) − (1962 − 1120) = 1944 − 842 = 1102 ± 92

Be effect: (3781 − 1882) − (1802 − 1120) = 1899 − 682 = 1217 ± 91

$\frac{Be}{C}$, observed = 1.1 ± 0.16

Weight C = 329.18

Weight Be = 337.26

$$\frac{\sigma_{Be}}{\sigma_C} = \frac{Eff_{Be}}{Eff_C} \times \frac{\left(\frac{Weight}{A}\right)_C}{\left(\frac{Weight}{A}\right)_{Be}} = 1.11 \times \frac{\frac{329.2}{12.01}}{\frac{337.18}{9.02}}$$

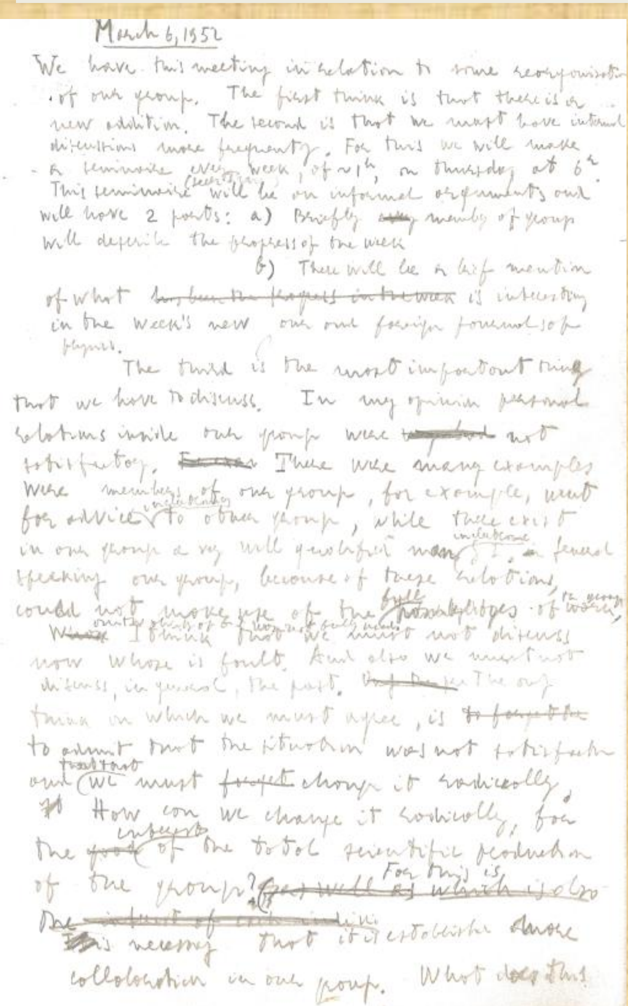
= 0.81 ± 0.12 Corrected

0.79 ± 0.12

Final results on meson production by neutrons

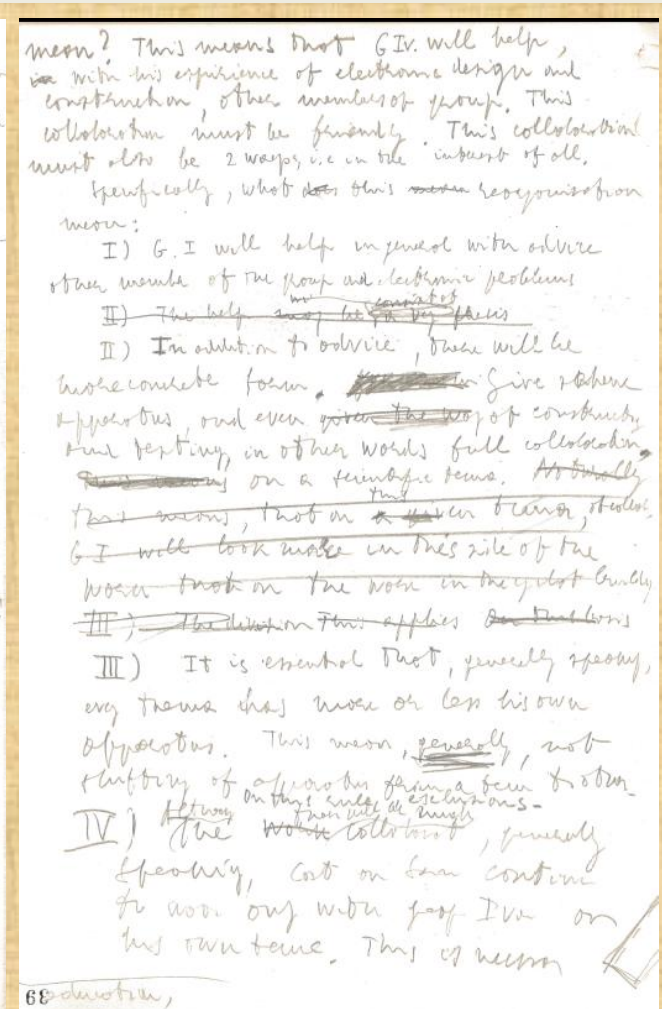
The speech of the Group Leader

A close collaboration between the various members of an experimental group is vital for the success of one experiment. However it is not always easy to ensure that the group collaborate efficiently as it is well known to every group leader; and the Pontecorvo's group was not an exception. Here is the draft of what Pontecorvo says in **the group meeting of March 6, 1952**:


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 6. This seminar will be an informal arguments and will have 2 parts: a) Briefly members of group will describe the progress of the week b) There will be a brief mention of what 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 not satisfactory. There were many examples, members of our group, for example, went for advice to other groups, while there exist in our group a very well qualified man, G.I. [illegible] speaking our group, because of these relations, could not make use of the [illegible]. I think that we must not discuss now whose is fault. And also we must not discuss, in general, the past. The only thing in which we must agree, is to admit that the situation was not satisfactory and we must change it radically. How can we change it radically, for interests of the total scientific production of the group? [illegible] It is necessary that it is established a more collaboration in our group. What does this


mean? This means that G.I. will help with his experience of electronic design and construction, other members of group. This collaboration must be friendly. This collaboration must also be 2 ways, i.e. in the interest of all.

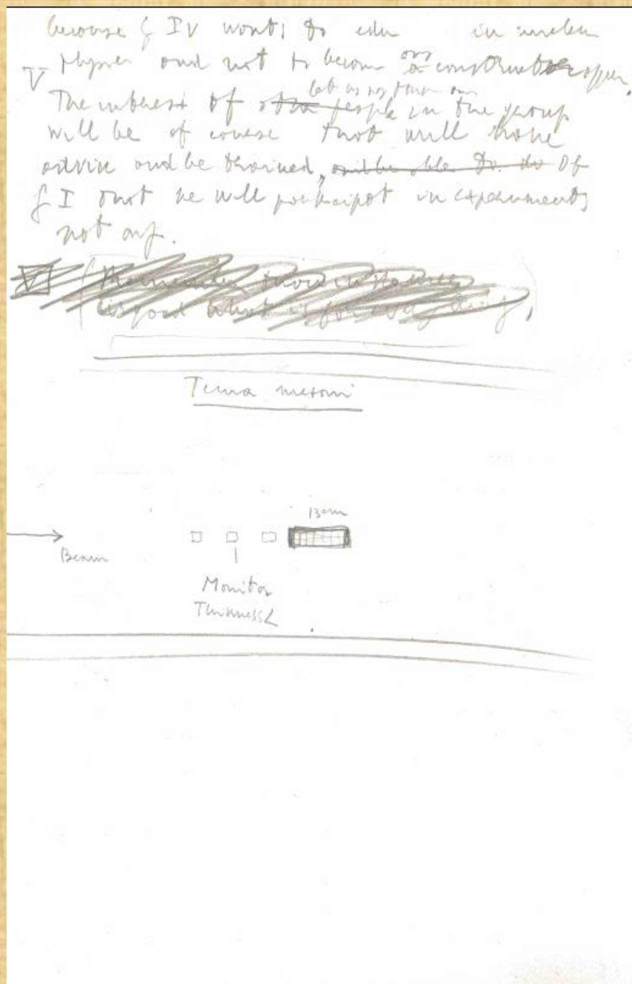
Specifically, what this reorganisation mean:

I) G.I. will help in general with advice other members of the group and electronic problems

II) In addition to advice, there will be more concrete form. Give scheme apparatus, and even [illegible] of construction and testing, in other words full collaboration on a scientific theme. [illegible] This means, that on a given theme, [illegible] G.I. will [illegible] this side of the work [illegible]

III) It is essential that, generally speaking, every theme has more or less his own apparatus. This mean, generally, not shifting of apparatus from a few to others [illegible]

IV) [illegible] generally speaking, can [illegible] continue to work only with group IV on his own theme. This is necessary [illegible] production,


because G. IV wants to [illegible] physics and not to become [illegible] constructor [illegible]

V The interest of [illegible] people in the group will be of course that will have advice and be trained, [illegible] G.I that he will participate in experiments not only.

Tema mesoni

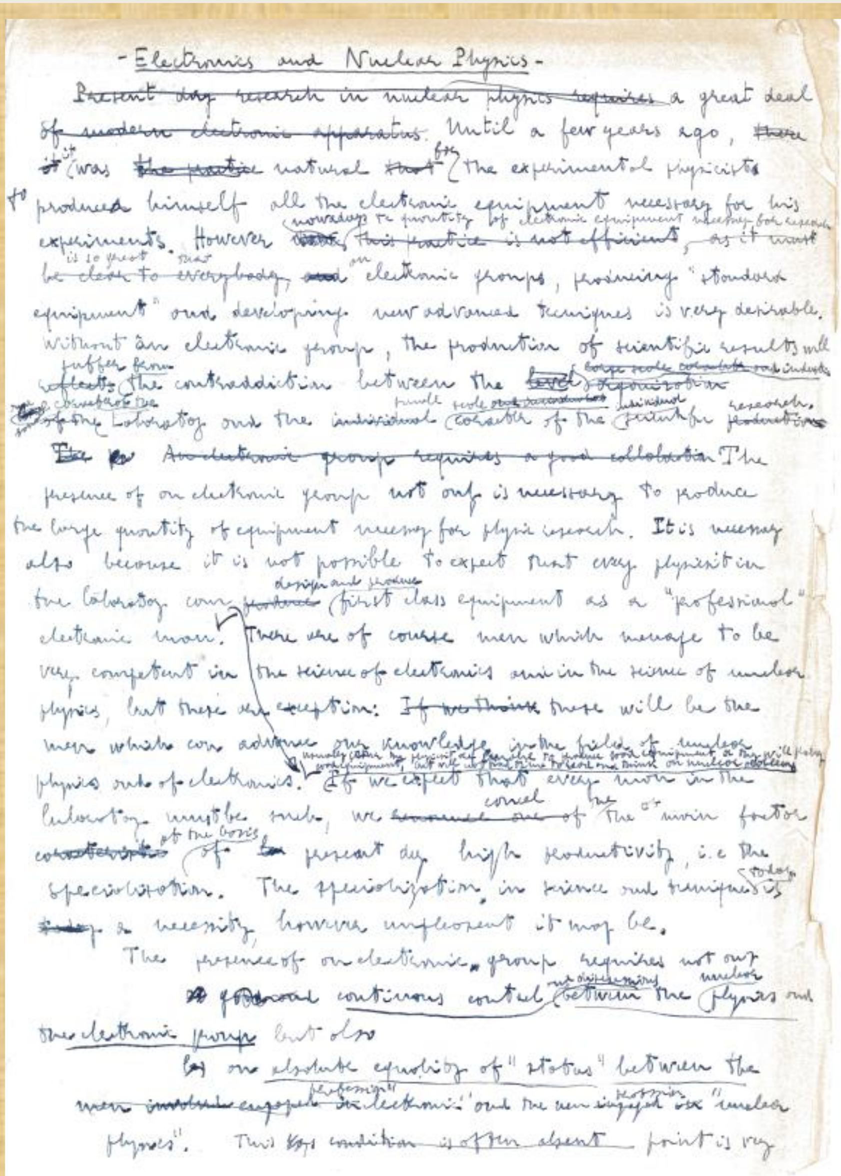
The speech of the Group Leader

March 6, 1952

We have this meeting in relation to some reorganization of our group.
The first thing is that there is a new addition.
The second is that we must have internal discussion more frequently. For this we will make a seminar every week, of ≈1^h , on Thursday at 6^h …omissis…
The third is the most important thing that we have to discuss. In my opinion personal relations inside our group were ~~very bad~~ not satisfactory. ***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.***
…omissis….. ***the situation was not satisfactory and we must change it radically, for the interest of the total scientific production of the group. For this is necessary that it is established more collaboration in our group.***

What does this mean? This means that G Iv. will help, with his experience of electronic design and contruction, other members of the group. This collaboration must also be 2 ways, i.e. in the interest of all. Specifically, what this reorganization means:
I) G.I. will help in general with advice other member of the group on electronic problems
II) In addition to advice, there will be more concrete form. Give scheme apparatus, and even of constructing and testing, in other words full collaboration on a scientific thema.
III) It is essential that, generally speaking, every thema has more or less his own apparatus. IV)….omississ, ….Cast (?) and Gean (?) continue to work only with George Ivan.. on his own theme. This is necessary because G Iv wants to work(?) in nuclear physics and not to be working on constructing apparatus.
V) The interest of other people in the group will be of course that will have advice and be trained, of G. I. that he will partecipate in experiments ….
~~VI) Remember …..is good what is for everybody~~

The problem of non-collaboration in the group between the electronics expert and the other members is perceived by Pontecorvo as a general problem in experiments of particle physics, very much present today even to a much greater extent. He then writes a document on how he thinks this problem should be solved.

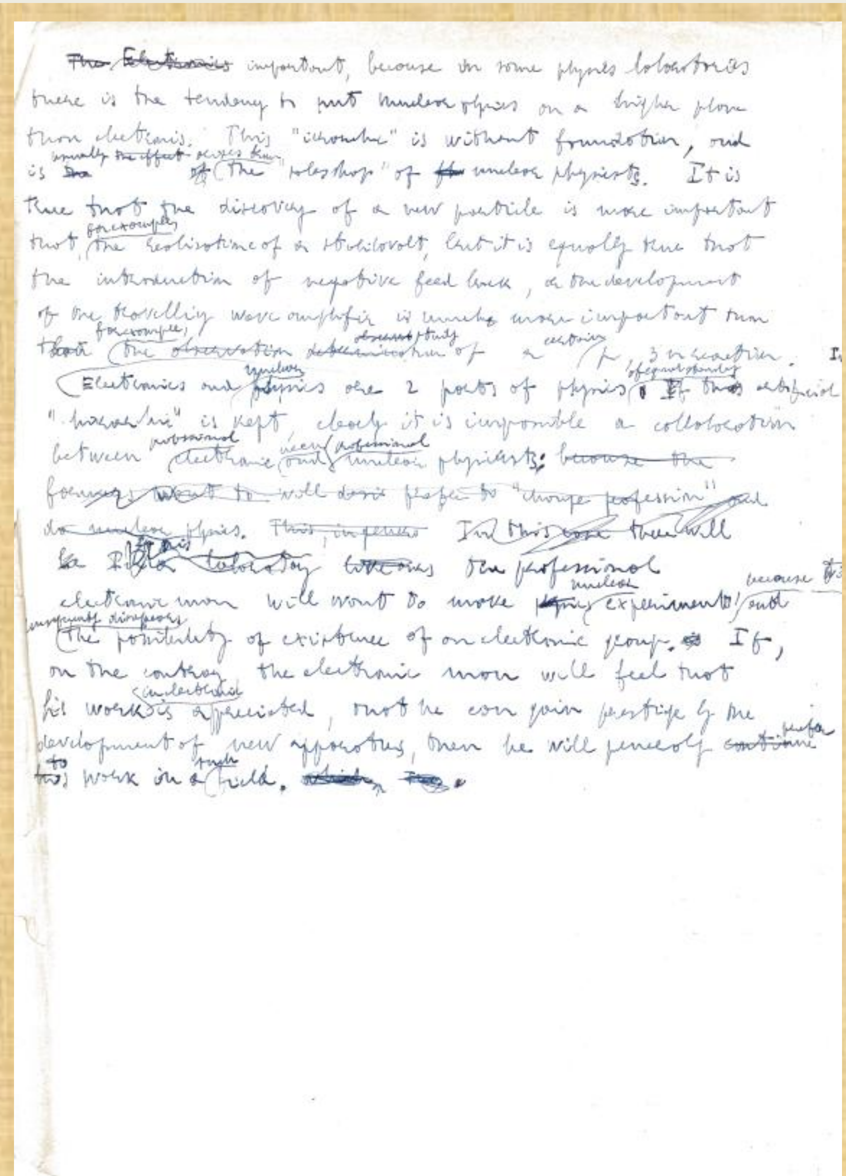


- Electronics and Nuclear Physics -

Present day research in nuclear physics requires a great deal of modern electronic apparatus. Until a few years ago, it was natural for the experimental physicists to produce himself all the electronic equipment necessary for his experiments. However nowadays the quantity of electronic equipment necessary for experiments is so great that electronic groups, producing "standard equipment" and developing new advanced techniques is very desirable. Without an electronic group, the production of scientific results will suffer from the contradiction between the large scale [illegible] of the laboratory and the small scale individual capacity of the scientist for research.

The presence of an electronic group not only is necessary to produce the large quantity of equipment necessary for physics research. It is necessary also because it is not possible to expect that every physicist in the laboratory can design and produce first class equipment as a "professional" electronic man. There are of course men which manage to be very competent in the science of electronics and in the science of nuclear physics, but these are exception: these will be the men which can advance our knowledge in the field of nuclear physics out of electronics. If we expect that every man in the laboratory must be such, we cancel one of the main factors of the basis of present day high productivity, i.e. the specialization. The specialization in science and techniques is today a necessity, however unpleasant it may be.

The presence of an electronic group requires not only continuous contact between the nuclear physicists and the electronic group but also an absolute equality of "status" between the men engaged professionally in electronics and the men engaged professionally in "nuclear physics". This condition is often absent. [illegible] point is very



important, because in some physics laboratories there is the tendency to put nuclear physics on a higher plane than electronics. This "[illegible]" is without foundation, and is usually [illegible] of the "[illegible]" of nuclear physicists. It is true that the discovery of a new particle is more important than, for example, the realisation of a Stabilovolt, but it is equally true that the introduction of negative feed back, or the development of the travelling wave amplifier is much more important than, for example, the [illegible] study of a certain [illegible] reaction. Electronics and nuclear physics are 2 parts of physics of equal standing. If this artificial "hierarchy" is kept, clearly it is impossible a collaboration between professional electronic and professional nuclear physicists; In this case [illegible] the professional electronic man will want to make nuclear experiments, and consequently disappears the possibility of existence of an electronic group. If, on the contrary, the electronic man will feel that his work is understood and appreciated, that he can gain prestige by the development of new apparatus, then he will generally prefer to work in such a field.

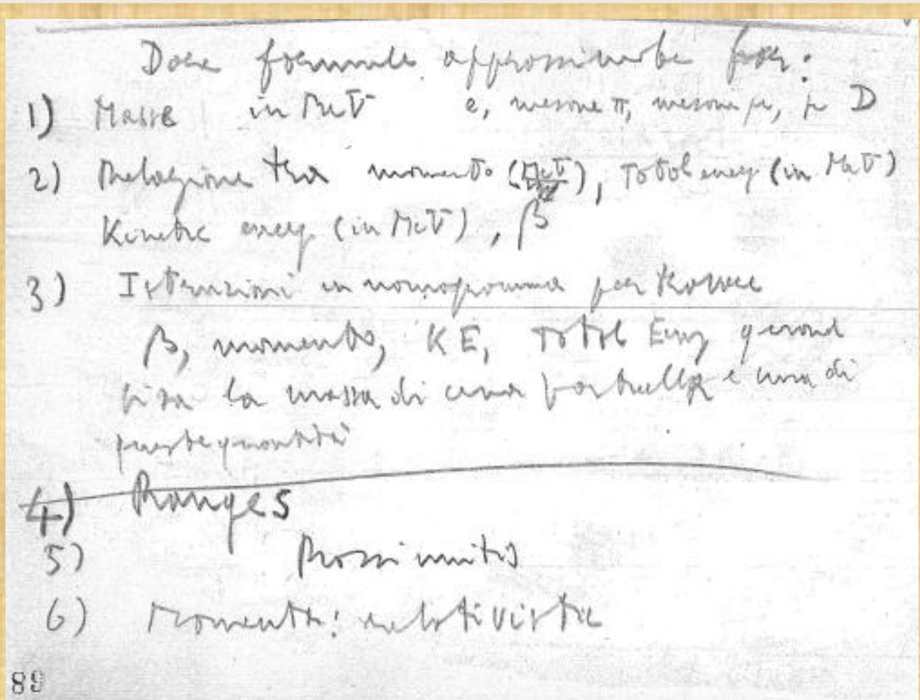
Draft of the document on the problem of collaboration between experts on electronics and in nuclear physics

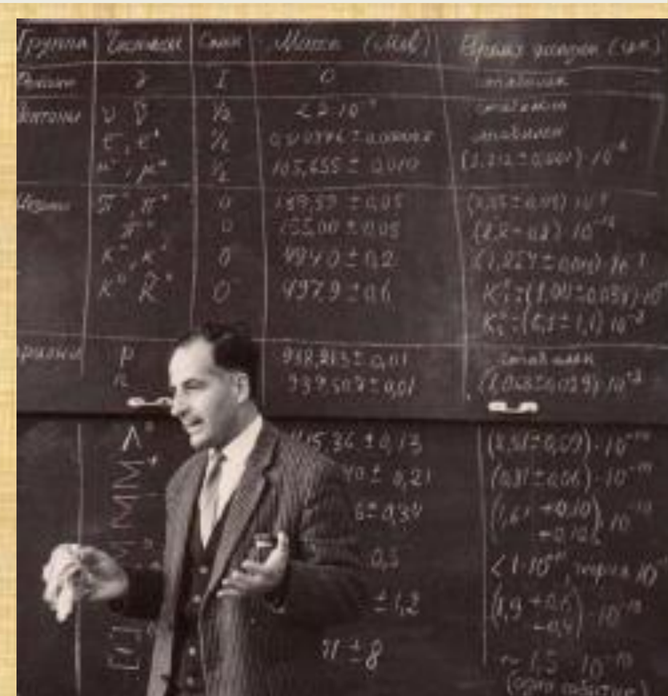
- <u>Electronics and Nuclear Physics</u> -

Until a few years ago, it was natural for the experimental physicist to produce himself all the electronics equipment necessary for his experiments. **However nowdays the quantity of electronic equipment necessary for research is so great that an electronic group, providing "standard equipment"and developing new advanced techniques is very desirable** …..omissis ….The presence of an electronic group not only is necessary to produce the large quantity of equipment necessary for physics research. It is necessary also because it is not possible to expect that every physicist in the laboratory can design and produce first class equipment as a "professional" man….omissis..**The specialization in science and techniques todays is a necessity, however unpleasent it may be.** The presence of on electronic group requires not only continuous control and discussions between the nuclear physicists and the electronic group but also an **<u>absolute equality of "status" between the</u> profession in "electronics" and the profession on "nuclear physics"**. This point is very important, because in some physics laboratories there is the tendency to put nuclear physics on higher plane then electronics…..omissis…..It is true that the discovery of a new particle is more important that, for example, the realization of a stabilovolt (?), but it is equally true that the introduction of negative feed-back, or the development of the travelling (?) wave amplifier is much more important that for example, the study of a certain p , 3n reaction. Electronics and nuclear physics are 2 parts of physics of equal importance (?). If this artificial behaviour (?) is kept, clearly it is impossible a collaboration between professional electronic men and professional nuclear physicists: the professional electronic man will want to move (?) nuclear experiments, and consequently disappears the possibility of existance of an electronic group. If, on the contrary, the electronic man will feel that his work in electronics is appreciated, that he can gain prestige by the development of new apparatus, then he will generally prefers to work in such field.

The Teacher

At the end of February 1952 Pontecorvo is probably doing some teaching because he writes in the Book this memo in "Italian". In the three following pages he writes these formulae and evaluates the ranges for proton and deuteron in Cu and Al at various energies



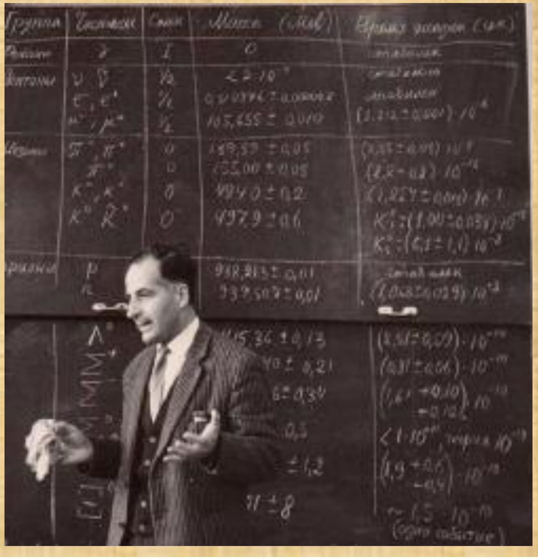


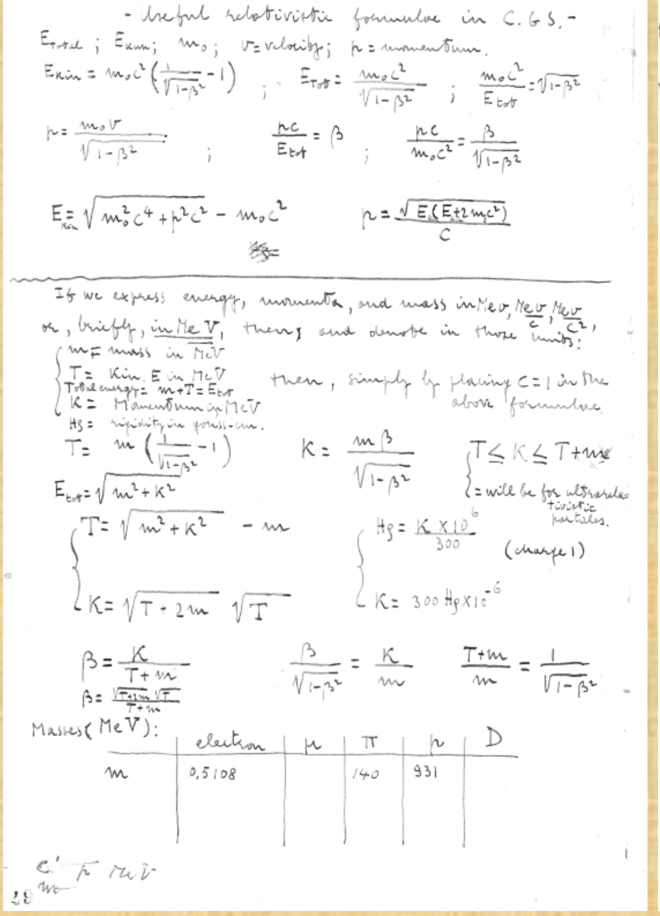
Dare formule approssimate ~~for~~ per:

1) Masse in MeV e, mesone π, mesone μ, p, D
2) Relazione tra momento (MeV/c), Total energy (in MeV), Kinetic energy (in MeV), β
3) Istruzioni in monogramma(?) per trovare β, momento, KE, Total energy quando si sa la massa di una particella e una di queste quantità
4) Ranges
5) Rossi units
6) Momenta: relativistic

The Teacher

Around the end of February 1952 Pontecorvo is probably doing some teaching and he writes in these three pages few relativistic relations and evaluates the ranges for proton and deuteron in Cu and Al at various energies





- Useful relativistic formulae in C.G.S. -

E_{Total} ; E_{kin}; m_0; v= velocity; p = momentum.

$E_{kin} = m_0c^2\left(\frac{1}{\sqrt{1-\beta^2}}-1\right)$; $E_{Tot} = \frac{m_0c^2}{\sqrt{1-\beta^2}}$; $\frac{m_0c^2}{E_{tot}} = \sqrt{1-\beta^2}$

$p = \frac{m_0 v}{\sqrt{1-\beta^2}}$; $\frac{pc}{E_{tot}} = \beta$; $\frac{pc}{m_0c^2} = \frac{\beta}{\sqrt{1-\beta^2}}$

$E_{kin} = \sqrt{m_0^2c^4 + p^2c^2} - m_0c^2$ $p = \frac{\sqrt{E(E+2m_0c^2)}}{c}$

If we express energy, momenta, and mass in MeV, MeV/c, MeV/c², or, briefly, in MeV, then, and denote in these units:

m = mass in MeV
T = Kin. E in MeV
Total energy = m+T = E_{tot}
K = Momentum in MeV
Hρ = rigidity in gauss-cm.

then, simply by placing c = 1 in the above formulae

$T = m\left(\frac{1}{\sqrt{1-\beta^2}}-1\right)$ $K = \frac{m\beta}{\sqrt{1-\beta^2}}$ $T \leq K \leq T+m$ (= will be for ultrarelativistic particles)

$E_{tot} = \sqrt{m^2+K^2}$

$T = \sqrt{m^2+K^2} - m$ $H\rho = \frac{K \times 10^6}{300}$ (charge 1)

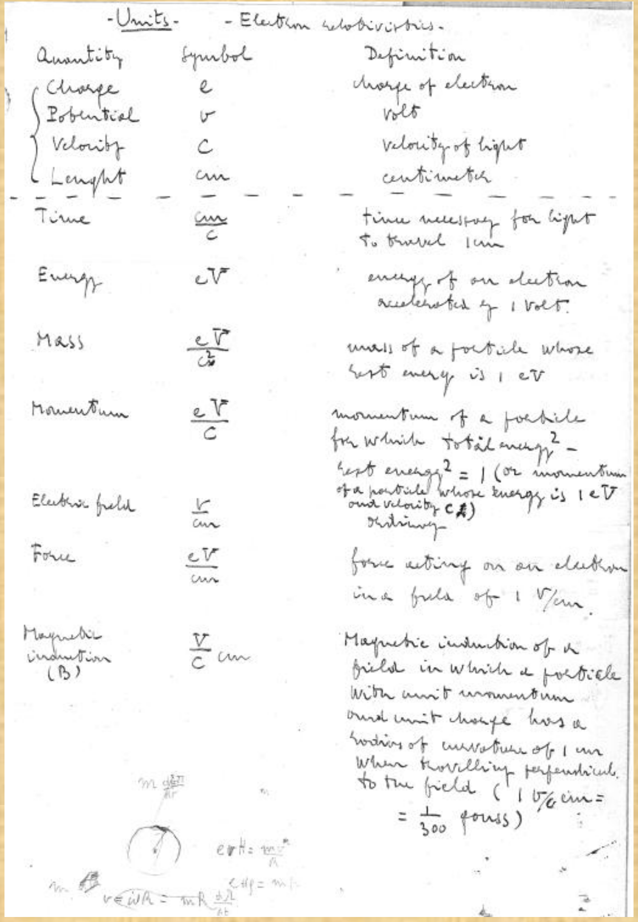
$K = \sqrt{T+2m}\sqrt{T}$ $K = 300 H\rho \times 10^{-6}$

$\beta = \frac{K}{T+m}$ $\frac{\beta}{\sqrt{1-\beta^2}} = \frac{K}{m}$ $\frac{T+m}{m} = \frac{1}{\sqrt{1-\beta^2}}$

$\beta = \frac{\sqrt{T+2m}\sqrt{T}}{T+m}$

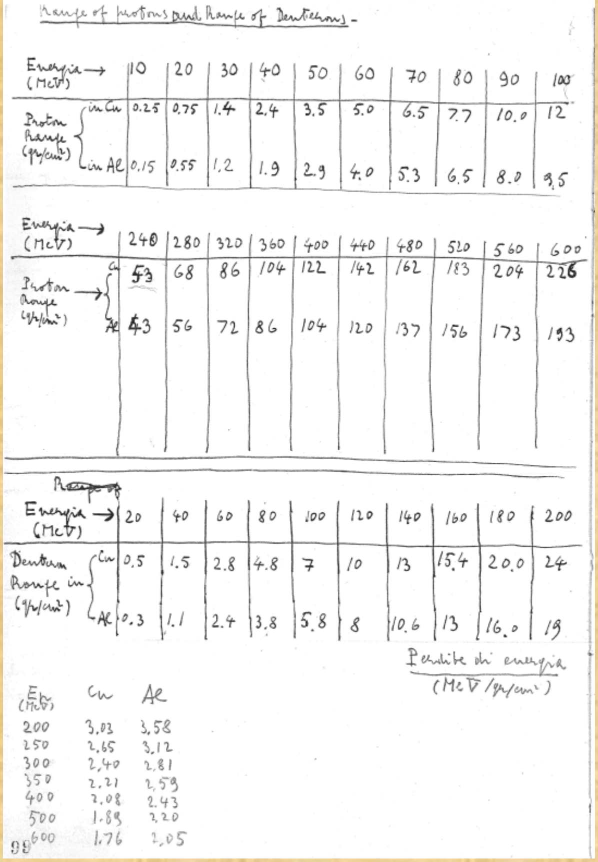
Masses (MeV):

	electron	μ	π	p	D
m	0,5108		140	931	



-Units- - Electron relativistics -

Quantity	Symbol	Definition
Charge	e	charge of electron
Potential	v	volt
Velocity	c	velocity of light
Lenght	cm	centimeter
Time	cm/c	time necessary for light to travel 1 cm
Energy	eV	energy of an electron accelerated by 1 volt
Mass	eV/c²	mass of a particle whose rest energy is 1 eV
Momentum	eV/c	momentum of a particle for which total energy² - rest energy² = 1 (or momentum of a particle whose energy is 1 eV and velocity c)
Electric field	V/cm	
Force	eV/cm	force acting on an electron in a field of 1 V/cm
Magnetic induction (B)	V/c cm	Magnetic induction of a field in which a particle with unit momentum and unit charge has a radius of curvature of 1 cm when travelling perpendicular to the field (1 V/c cm = 1/300 gauss)



Range of protons and Range of Deuterons -

Energia → (MeV)	10	20	30	40	50	60	70	80	90	100
Proton Range (gr/cm²) in Cu	0.25	0.75	1.4	2.4	3.5	5.0	6.5	7.7	10.0	12
Proton Range (gr/cm²) in Al	0.15	0.55	1.2	1.9	2.9	4.0	5.3	6.5	8.0	9.5

Energia → (MeV)	240	280	320	360	400	440	480	520	560	600
Proton Range (gr/cm²) Cu	53	68	86	104	122	142	162	183	204	226
Proton Range (gr/cm²) Al	43	56	72	86	104	120	137	156	173	193

Energia → (MeV)	20	40	60	80	100	120	140	160	180	200
Deuteron Range in (gr/cm²) Cu	0.5	1.5	2.8	4.8	7	10	13	15.4	20.0	24
Deuteron Range in (gr/cm²) Al	0.3	1.1	2.4	3.8	5.8	8	10.6	13	16.0	19

Perdite di energia (MeV/gr/cm²)

E (MeV)	Cu	Al
200	3.03	3.58
250	2.65	3.12
300	2.40	2.81
350	2.21	2.59
400	2.08	2.43
500	1.89	2.20
600	1.76	2.05

In this book there is the story of some experiments on meson production by neutrons and protons both on complex nuclei and protons performed by Bruno Maximovich Pontecorvo and his small group of young physicists at the Dubna Cyclotron. He continues to use this book for drafts, sketchs, notes and mainly as logbook for data taking of the experiments performed during six months from 14 September 1951 until end of ($\geq$ 24th) March 1952. The last few pages are a draft of the paper *"Production of neutral mesons by neutrons"*, which concludes the experiment proposed at the beginning of reversed side of the book, and published (see next slide) as internal report in Russian (*B.M.Pontecorvo, G.I.Selivanov, RINP,1951*).

- *Production of neutral mesons by neutrons* -

Schema:

A) Introduction B) *Apparatus* C) *Absolute experiment in Carb* ~~D) Relative measurements Discussion in relation to production of mesons~~ E) *Relative measurements* F) *Discussion a) production b)* λ
G) *Conclusions -* *- Spectrum*

Introduction -

While a considerable amount of data have been published (1) *in the last years on the production of mesons by protons from accelerators , the production of ~~charged~~ mesons by neutrons has been so far only the object of a short communication* (2) *~~and the production of neutral mesons by neutrons so far had not been observed~~. The following table summarize the present day information on this subject.*

Table I

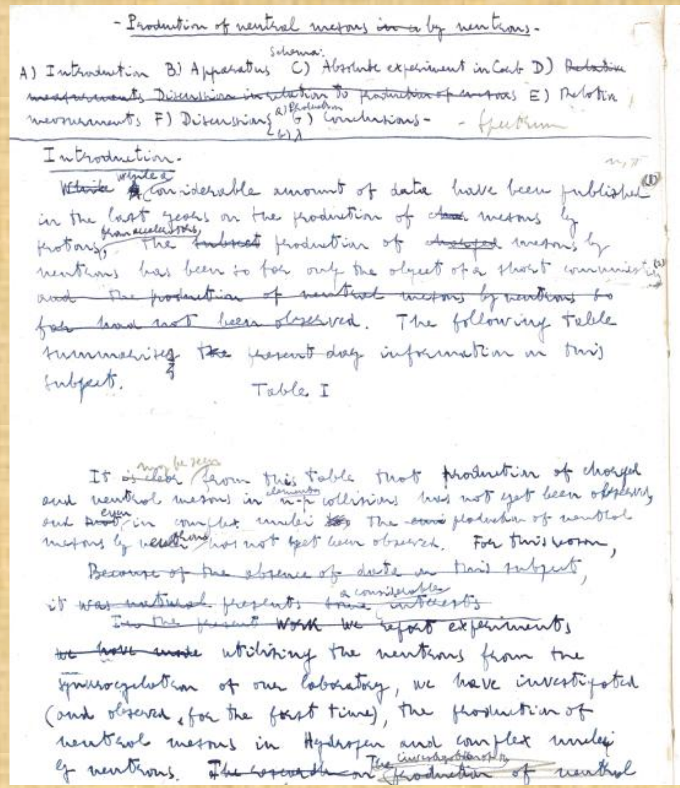
It ~~is clear~~ may be seen from this table that production of charged and neutral mesons in elementary n-p collisions has not yet been observed, and ~~not~~ even in complex nuclei. The production of neutral mesons by neutrons has not yet been observed. For this reason, ~~Because of the absence of data in this subject, it was natural presents some a considerable interests~~ ~~In the present work we report experiments we have made~~ utilizing the neutrons from the syncrocyclotron of our laboratory, we have investigated (and observed for the first time), the production of neutral mesons in Hydrogen and complex nuclei by neutrons.

First internal reports on π-mesons production

The results of all experiments carried on by Bruno Maximovich Pontecorvo with his group of young researchers in the period 1951-1954 at the five-meter cyclotron were published as internal reports in Russian, some of those were also published later in 1955.

In these early experiments the production of single charged and neutral π mesons with proton and neutron beams on proton and complex nuclei were performed:

The production of π^0 with a neutron beam on protons and on complex nuclei was studied for the first time in the world *(B.M.Pontecorvo, G.I.Selivanov, RINP,1951)* and *(B.M.Pontecorvo, G.I.Selivanov, RINP,1952; Dokl.Acad. Nauk SSSR,102,253 (1955)).*


- Production of neutral mesons by neutrons -

Schema:

A) Introduction B) Apparatus C) Absolute experiment in Carb D) ~~Relative measurements Discussion in relation to production of mesons~~ E) Relative measurements F) Discussions G) Conclusions -

Introduction.

~~While~~ Whilst a considerable amount of data have been published (1) in the last years on the production of ~~charged~~ mesons by protons, ~~The~~ ~~indirect~~ production of ~~charged~~ mesons by neutrons has been so far only the object of a short communication (2) ~~and the production of neutral mesons by neutrons so far had not been observed~~. The following table summarizing ~~the~~ present day information on this subject.

Table I

It ~~is clear~~ may be seen from this table that production of charged and neutral mesons in n-p collisions has not yet been observed and ~~most~~ even in complex nuclei ~~the~~ The production of neutral mesons by neutrons has not yet been observed. For this reason,

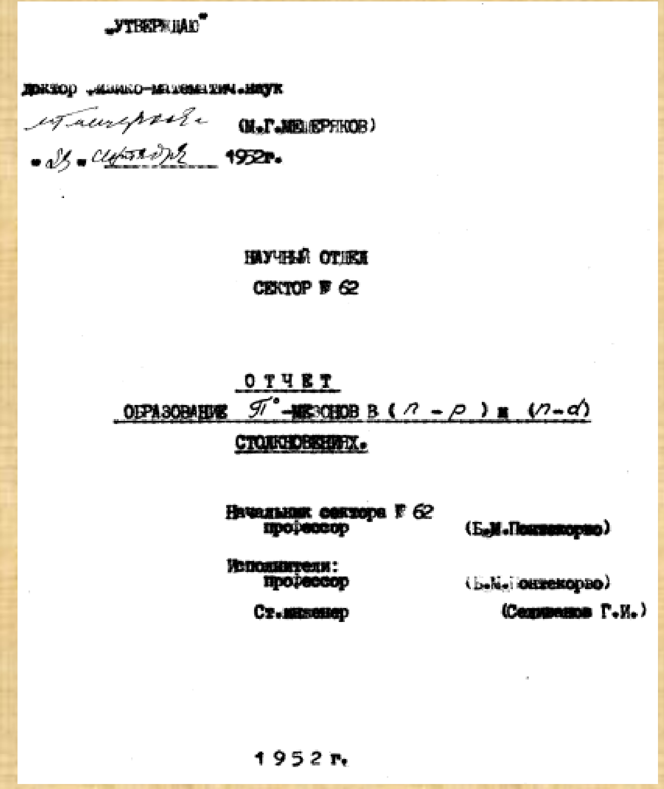
~~Because of the absence of data on this subject,~~

it ~~was natural~~ presents ~~true~~ a considerable interests

~~In the present work we report~~ experiments

~~we have made~~ utilizing the neutrons from the synchrocyclotron of our laboratory, we have investigated (and observed, for the first time), the production of neutral mesons in Hydrogen and complex nuclei by neutrons. ~~The research on~~ The production of neutral

Draft in English from the Notebook (~11/18 March 1952)


„УТВЕРЖДАЮ"

Доктор физико-математич. наук

(М.Г.Мещеряков)

1952г.

НАУЧНЫЙ ОТДЕЛ

СЕКТОР № 62

ОТЧЕТ

ОБРАЗОВАНИЕ π^0-МЕЗОНОВ В (n - p) и (n-d) СТОЛКНОВЕНИЯХ.

Начальник сектора № 62 профессор (Б.М.Понтекорво)

Исполнители: профессор (Б.М.Понтекорво)

Ст.инженер (Селиванов Г.И.)

1 9 5 2 г.

25 September 1952

REPORT

Production of π^0 mesons in (n-p) and (n-d) collisions

Section leader
Professor (B.M.Pontecorvo)

Executors:
Professor (B.M.Pontecorvo)
Engineer (Selivanov G.I.)

Internal Report in Russian dated September 25,1952 kindly provided to us by Gil Pontecorvo

First internal reports on π-mesons production

АКАДЕМИЯ НАУК СОЮЗА СОВЕТСКИХ СОЦИАЛИСТИЧЕСКИХ РЕСПУБЛИК

"УТВЕРЖДАЮ"

Начальник Гидротехнической лаборатории АН СССР
доктор физико-матем. наук

/М.Г.Мещеряков/

" " марта 1952 года.

ОТЧЕТ

ПОПЫТКА ДЕТЕКТИРОВАТЬ ЯДЕРНОЕ РАССЕЯНИЕ π -МЕЗОНОВ С ОБМЕНОМ ЗАРЯДА ПРИ ПОМОЩИ РАДИОАКТИВНЫХ ИНДИКАТОРОВ.

Руководитель: проф. Понтекорво Б.
Исполнители: проф. Понтекорво Б.
инж. Мухин А.И.

March 1952

REPORT

Detection of charge exchange scattering of π mesons on nuclei by the method of radioactive indicators

Leader: Prof. Pontecorvo B.
Executors: Prof. Pontecorvo B.
Eng. Mukhin A.I.

Internal Report in Russian dated March 1952 kindly provided to us by Gil Pontecorvo

Attempt to detect the charge exchange scattering of π mesons by the method of radioactive indicators

Introduction

Draft in English from the Notebook (~ October 5 – December 25, 1951)

Attempt to detect the charge exchange scattering of π mesons by the method of radioactive indicators

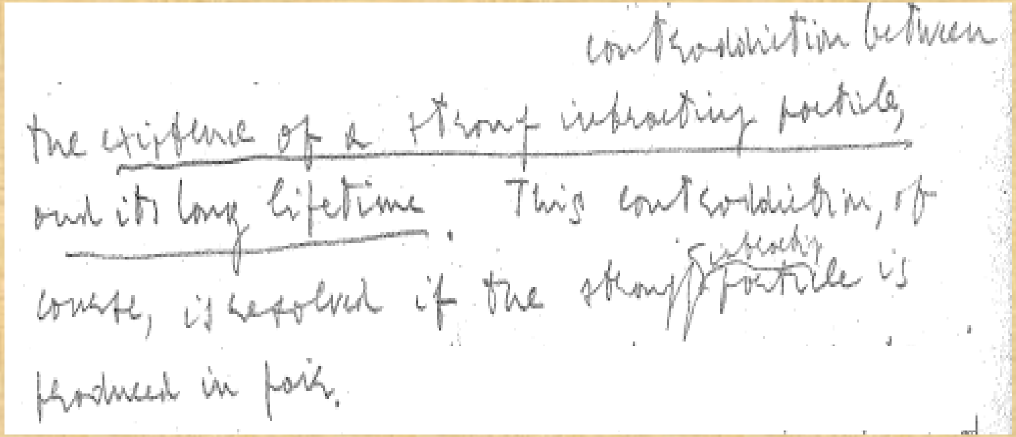
Introduction

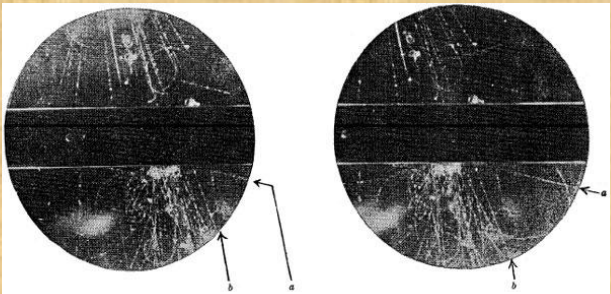
The interaction of π mesons with nuclei was first investigated in the cosmic ray region, with conflicting results. Brown(1) found an interaction mean free path in photographic plates for the π mesons produced in showers of relativistic particles of the order of the "geometrical" mean free path, while Piccioni, with counter techniques, obtained a mean free path > 10 times the geometrical mean free path. This discrepancy was removed when work with artificial π mesons from accelerator was initiated....omissis... It occurred(?) to us that nuclear interaction with cross section of this order could be detected with the method of radioactive indicators. In fact with the meson intensities of the order of 10^4-10^5/cm²/sec, which are available in a beam from the cyclotron of our laboratory it can be estimated that in favorable circumstances it is possible to detect in light elements the production of radioelement with cross section only 10^{-27} cm². This report will be mainly concerned with an attempt to detect the reaction $\pi^+ + B^{11} \rightarrow \pi^0 + C^{11}$ from the radioactive indicators.

($^{11}C \rightarrow {}^{11}B + e^+ + \nu + 0.96$MeV with 20.3 min. half-life)

Strange Particles

The experiments on π meson-nucleon interaction performed at Dubna in the early 50s are certainly of great interest for Pontecorvo in understanding, at least phenomenologically, the strong interactions in the π meson-nucleon scattering.
However **he was very excited by discovery in the 1947 of unstable new baryon and meson particles (the so called V particles)** and, as we have seen at page 8 of his notebook, already at the end of 1950, he was puzzled by the


contradiction between
the existence of a strong interacting particle,
and its long lifetime. This contradiction, of
course, is resolved if the strong particle is
produced in pair.



Cloud-chamber photograph of a V^0 particle decaying into two charged particles (G.D.Rochester, C.C.Butler, Nature 160, 855 (1947))

In the "Recollections on the establishment of the weak interaction notion" *(B.Pontecorvo, JINR Preprint E1-85-583, Dubna, 1985)* he writes: *"Since 1947 I had been expecting new weak processes, so that I was very happy about all this. I felt that the notion of weak interaction became wider once again, but in new process. ..omissis.....On the basis of simple arguments I introduced* ***(B.Pontecorvo, JETP, 1955, vol.29, p.140, with quotations on previous papers.)*** *, independently of Pais* ***(Pais A., Phys.Rev., 1952, vol86, p.655)*** *the idea of pair production of the new particles, more exactly the pair production of hyperons and kaons."*

Strange Particles

In one internal report(*) dated 1953, Pontecorvo and his group discuss how and why the production of τ and V particles should be studied:

Тема 48. Методы регистрации частиц класса "τ" и "V" с помощью электронных устройств и камеры Вильсона.

Руководитель: Понтекорво Б.М.

Theme 48. Detection method of the class of particles "τ" and "V" with electronic detectors and Wilson chamber.

Group leader: Pontecorvo B.M.

In this report there are several discussions presented by members of the group on the possible detection techniques of these particles while at point 2 Pontecorvo himself describes the reasons of interest of such experiment.

2. О процессах образования тяжелых мезонов и V -частиц.

Исполнитель: Понтекорво Б.М.

Написан отчет[1)], в котором излагаются некоторые замечания феноменологического характера о процессах образования тяжелых мезонов и V -частиц. Основные идеи этой работы обсуждались на семинаре в нашей лаборатории в 1951г. Хотя представленные рассмотрения имеют характер поисков, они могут помочь сформулировать рабочие гипотезы при интерпретации экспериментальных данных и при обсуждении возможности постановки экспериментов по образованию новых частиц.

Выводы работы следующие:

1) Тот факт, что в соударениях при высокой энергии с большой вероятностью образуются мезоны (мезоны класса τ), распадающиеся с продолжительным временем жизни на π -мезоны, указывает на то, что рождение этих мезонов не может происходить по схеме:

$(\mathcal{N}) \rightarrow (\mathcal{N}) + (\tau)$ ($\mathcal{N} \equiv$ нуклон)

2) Аналогично, тот факт, что в соударениях при высокой энергии с большой вероятностью образуются частицы (тяжелые нуклоны класса V), распадающиеся с продолжительным временем жизни на нуклоны и π -мезоны, указывает на то, что рождение этих частиц не может происходить по схеме:

$(\mathcal{N}) \rightarrow (V) + (\pi)$.

3) Предполагается, что мезоны класса τ и частицы класса V появляются вместе согласно схеме:

$(\mathcal{N}) \rightarrow (V) + (\tau)$ (1)

Таким образом одновременно решаются трудности, связанные с продолжительным временем жизни частиц класса V и мезонов класса τ. Кроме того, эта схема подразумевает сильное взаимодействие между нуклонами и V -частицами.

4) Если схема (1) верна, то следует ожидать, что в благоприятных условиях должны осуществляться квази-стабильные системы из нуклонов и V -частиц.

Некоторые экспериментальные указания о справедливости этих выводов появились в литературе[2)].

Ниже мы обсудим вопросы, связанные с порогами образования V°-частиц при предположении, что в схеме (1) под V подразумевается известная V°-частица.

Очевидно, что сечение реакции

$\mathcal{N} + \mathcal{N} \rightarrow \mathcal{N} + V$

должно быть крайне малым при справедливости схемы (1). Сле-

2. On the production of heavy mesons and V - particles.

Executor: Pontecorvo B.M.

A report has been written *[B. Pontecorvo, Report numb. 850, 1953]*, in which certain comments of phenomenological character concerning the production of heavy mesons and V -particles are presented. **The main ideas of this work have been discussed at the seminar of our laboratory in 1951.** Although the issues presented are of a search nature, they may help in formulating operative hypotheses for interpretation of experimental data and the discussion of future experiments relevant to the production of new particles.

The conclusions are the following:

1. The fact that high energy collisions with a **high probability result in the production of mesons** (mesons of the τ class), **decaying with a long lifetime** into π-mesons indicates that **the production of such mesons cannot proceed according** to the following scheme: ***(N)→ (N) + (τ) (N ≡ nucleon).***

2. Similarly, the fact that high energy collisions with a **high probability result in the production of particles** (heavy nucleons of the V class), **decaying with a long lifetime** into nucleons and π-mesons indicates that the **production of these particles cannot proceed according** to the following scheme: ***(N)→ (V) + (π).***

3. The assumption is made that mesons of the class and particles of the V class appear together according to the scheme:

(N)→ (V) + (τ) **(1)**

Thus, **difficulties related to the long lifetime of particles of the V class and of mesons of the τ class are resolved simultaneously**.

Moreover, this scheme implies strong interaction between nucleons and V -particles.

4. If the scheme (1) holds true, then quasi-stable systems of nucleons and V -particles can be expected to be realized in favorable conditions.

Certain experimental indications of the validity of the above conclusions have appeared in the literature [W.B.Fowler et al., Phys.Rev 91 (1953) 1062].

Below we shall discuss issues related to the production thresholds of V^0-particles under the assumption that V in the scheme (1) is considered to be a known V^0-particle.

Evidently, the **cross section of reaction**

N+N → N+V

should be extremely small, if the scheme (1) is valid.

(*)(kindly provided and partially translated for us from Russian by the son Gil Pontecorvo)

Strange Particles

In 1953, the fact that particles produced via strong interaction and decaying with a long lifetime must be produced in pair was not completely clear from an experimental point of view.

As usual, the theoretical physicist Pontecorvo, as brilliant experimenter, decides to clarify this point by himself :

an experiment was done trying to observe the formation of Λ^0–particles in collisions of 670 MeV protons with carbon nuclei ***(Baladin M.P., Balashov B.D., Zhukov V.A., Pontecorvo B.M., Selivanov G.I. Report of the Inst. for Nuclear Problem, Acad. Sci. USSR, 1954).*** The conclusion of the experiment was that:

> "*The small value of the cross section for the formation of Λ^0 particles in the interaction of protons with an energy of 670 MeV with complex nuclei agrees with the hypothesis of the fundamental transformation of a nucleon according to the scheme (N)* $\leftrightarrow$ (Λ^0) + (heavy meson)."

The production in pair of V-particles and heavy mesons was later observed in $\pi^- p$ collision with π^- of 1.5 BeV from the BNL Cosmotron by W.B.Fowler et al. *(Phys. Rev. 93, 861 (1954))*

PHYSICAL REVIEW VOLUME 93, NUMBER 4 FEBRUARY 15, 1954

Production of Heavy Unstable Particles by Negative Pions*

W. B. Fowler, R. P. Shutt, A. M. Thorndike, and W. L. Whittemore
Brookhaven National Laboratory, Upton, New York

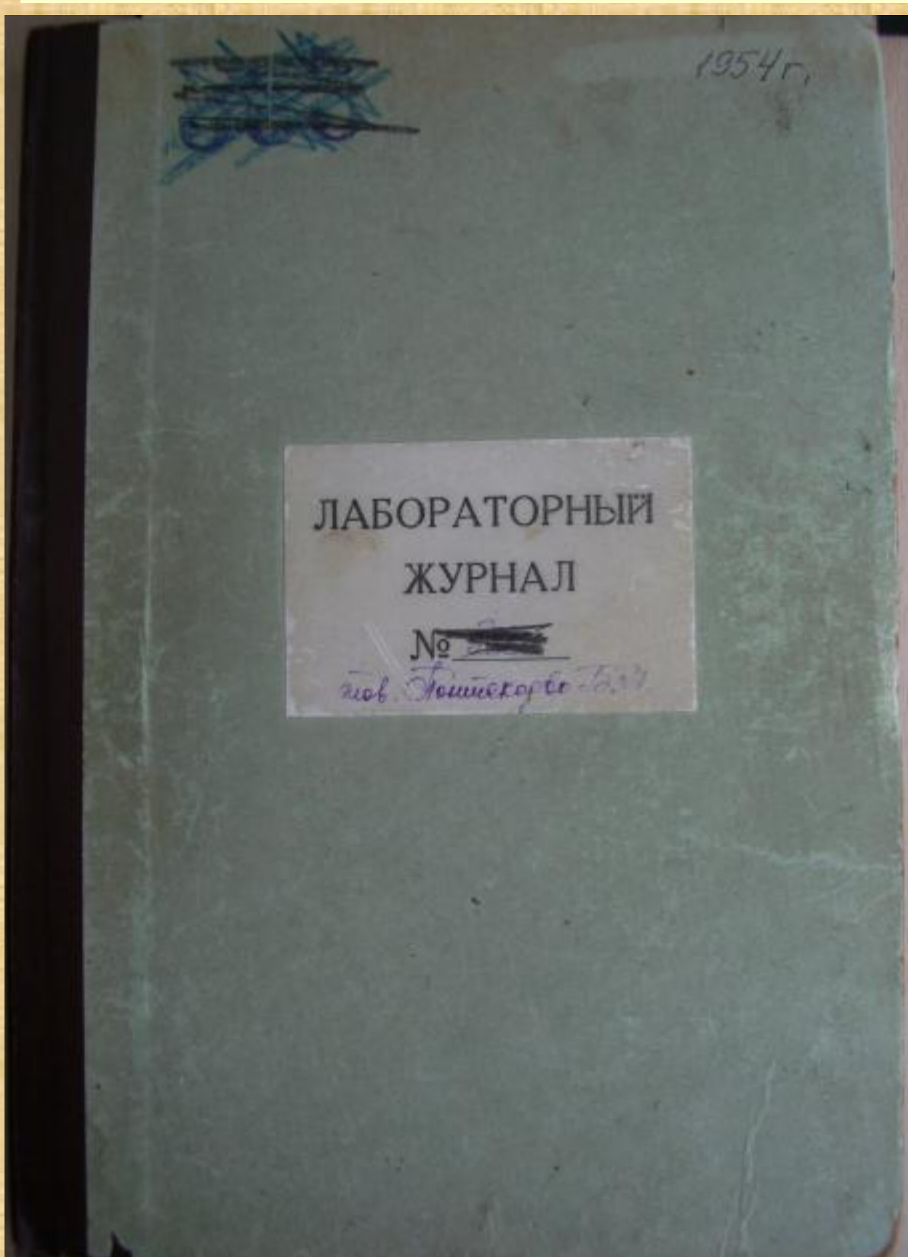
(Received November 10, 1953)

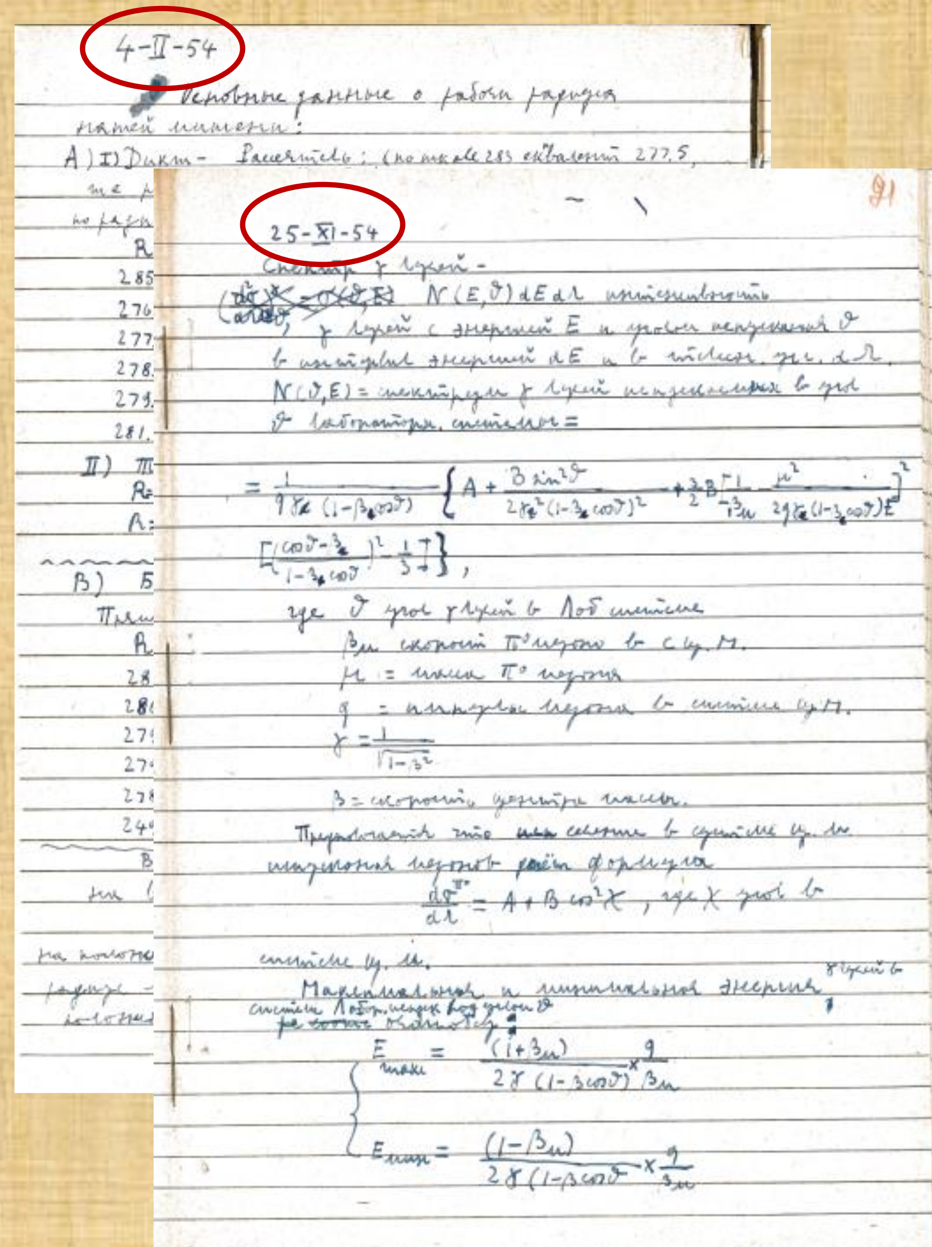
The important contributions given by Pontecorvo to the problem of understanding the properties of the "strange particles" are not enough acknowledged to him by the scientific community.

He was probably the first to have the intuition that the contradictory behavior of these strange particles can be explained if are produced in pair.

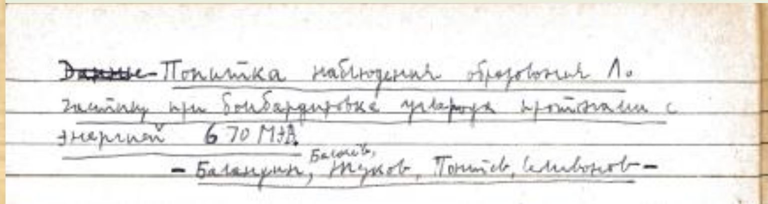
Unfortunately this idea remained hidden in internal reports written in Russian, not accessible for long time to the vast community of physicists outside the Soviet Union.

We have another Logbook/Notebook which covers the period from February to November 1954. Thanks to Gil Pontecorvo who kindly gave us. This Notebook is written in Russian.

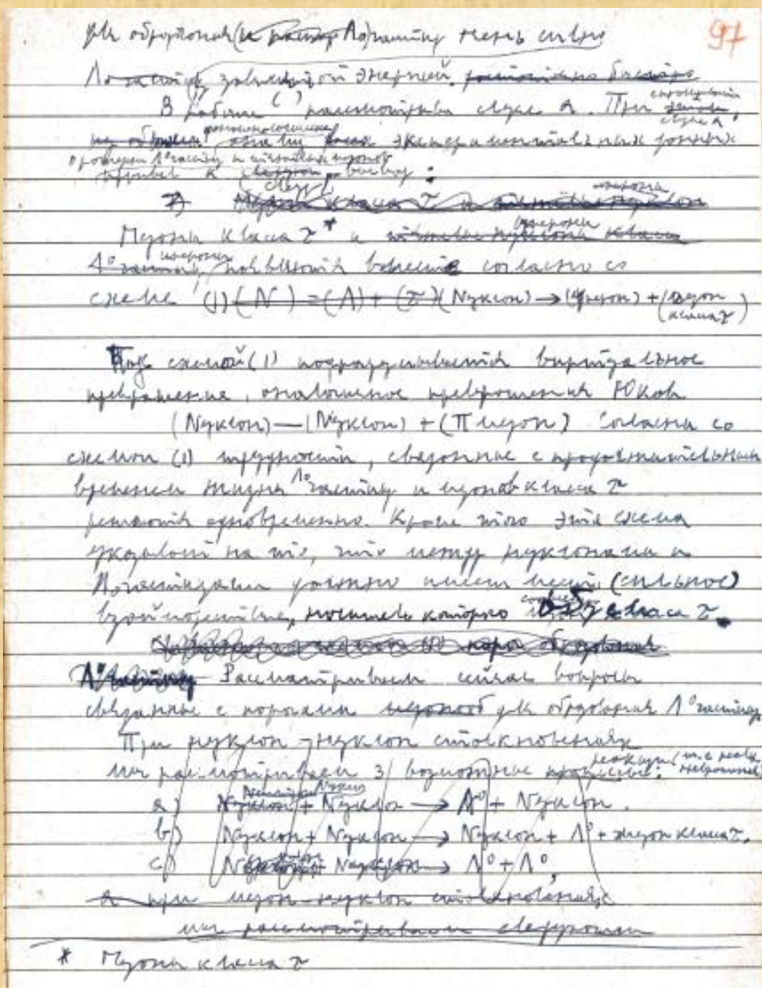


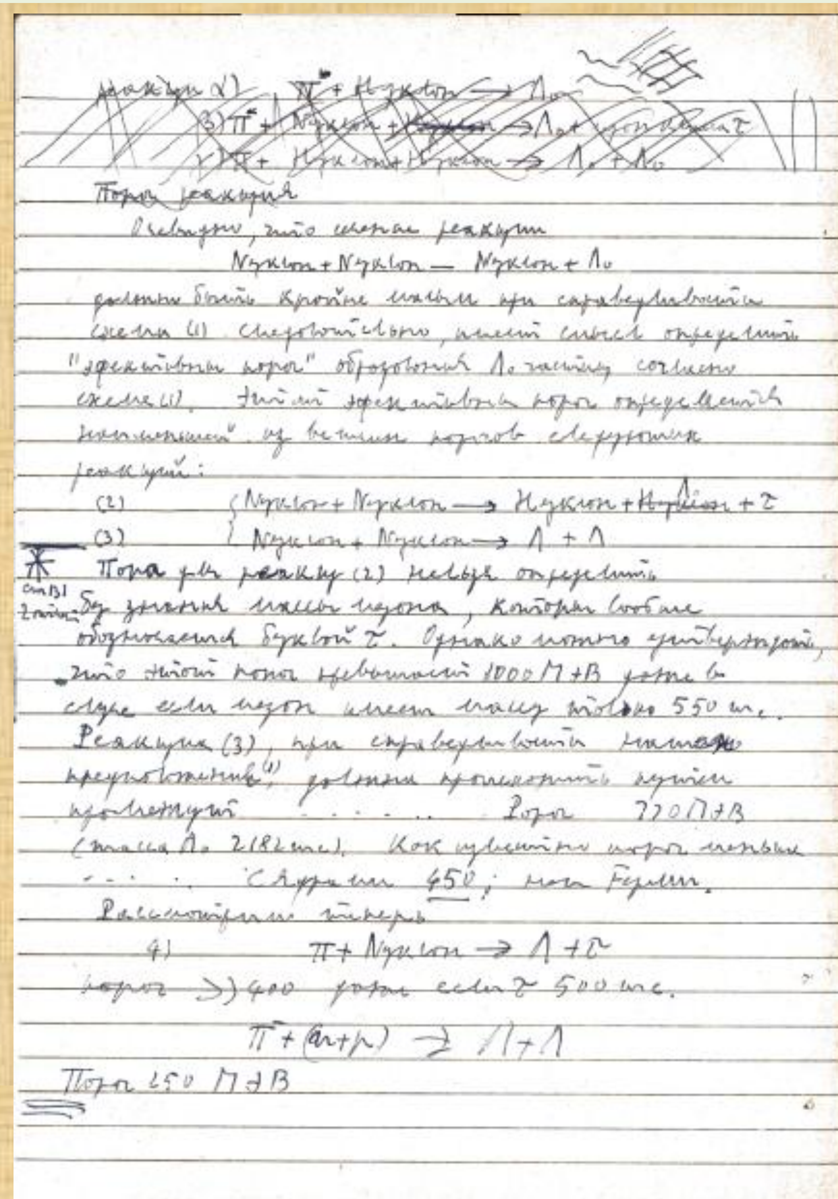


I can't read Russian, however at the end of the Notebook there is a the draft that looks to me the draft of the published paper ***"The possibility of the formation of Λ^0-particles by protons with energies up to 670 MeV"*** *(Baladin M.P.,Balashov B.D.,Zhukov V.A., Pontecorvo B.M., Selivanov G.I., Report of the Inst. for Nuclear Problem, Acad.Sci. USSR,1954.)*


Попытка наблюдения образования Λ_0 частицы при бомбардировке углерода протонами с энергией 670 МэВ

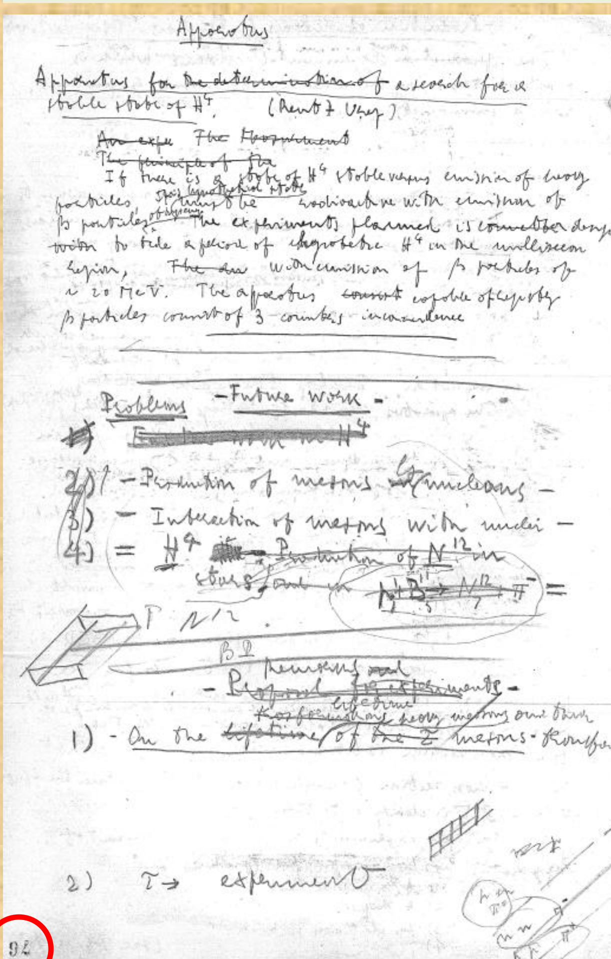
— Баладин, Балашов, Жуков, Понтекорво, Селиванов —





Coming back to first Notebook, very interesting is what I found on page 76 (reversed) !

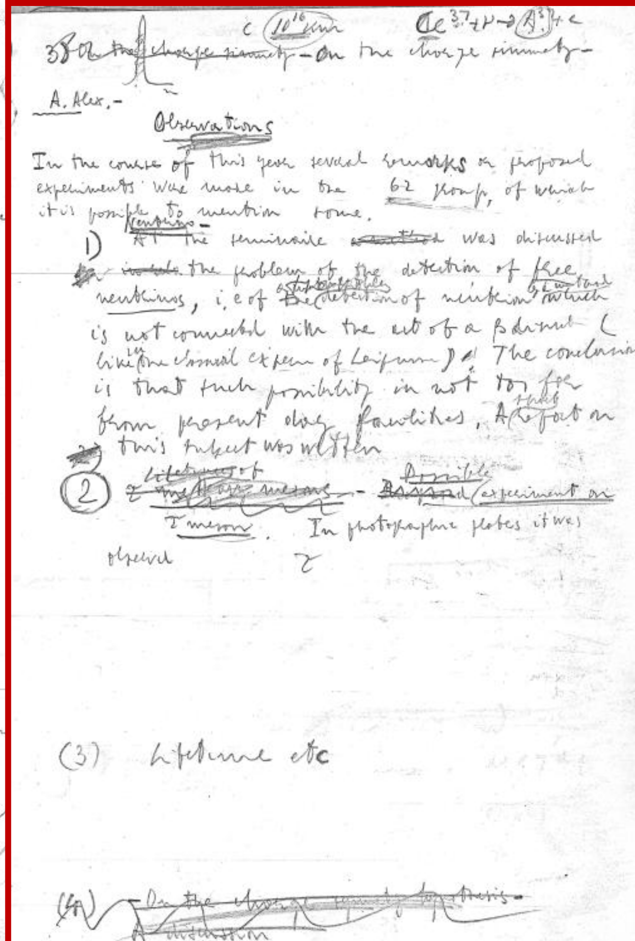
This page was written between December 25,1951 and January 30,1952



Remarks ~~and~~
~~Proposal for experiments~~ -

1) -On the ~~lifetime transformations~~ lifetime of ~~the τ mesons~~ heavy mesons and their transformation -

2) $\tau \rightarrow$ experiment



c 10^{16} Km (*) $Cl^{37} + \nu \rightarrow Ar^{37} + e$

~~3) On the charge symmetry~~ -On the charge symmetry

A. Alex.-

Observations

In the course of this year several remarks or proposed experiments were made in the 62 group, of which it is possible to mention some.

Neutrino -

1) *At the seminaire ~~a method~~ was discussed ~~in rela~~ the problem of the detection of free neutrinos, i.e. of a .... detection of neutrino, a method which is not connected with the act of a β disintegration (like in the classical experiment of Leipunski) The conclusion is that such possibility is not too far from present day facilities, A short report on this subject was written*

(2) ~~*Lifetime of τ mes Heavy mesons*~~ - *Possible experiment on τ meson.*

In photographic plates it was observed τ

(3) *Lifetime etc.*

~~(4) - On the charge symmetry hypothesis~~
~~A discussion~~

(*) H.Bethe and R.Peierls in Nature 133,532-532 (07 April 1934) evaluated an upper limit for the cross section of the neutrino interaction with matter and they wrote *"For an (neutrino) energy of 2*3x10⁶ volts….σ < 10⁻⁴⁴ cm²(corresponding to a penetrating power of 10¹⁶ Km in solid matter) It is therefore absolutely impossible to observe process of this kind with neutrinos created in nuclear transformation."*

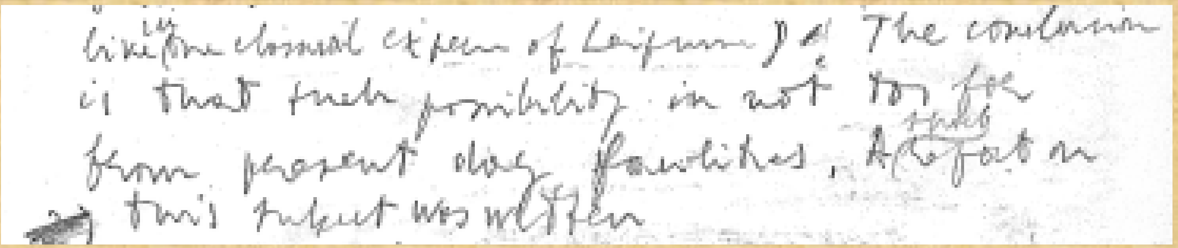
Free neutrino detection

I guess that when Pontecorvo is writing, at the end of 1951, in the top right corner of the page 76 (reversed) of the Notebook:

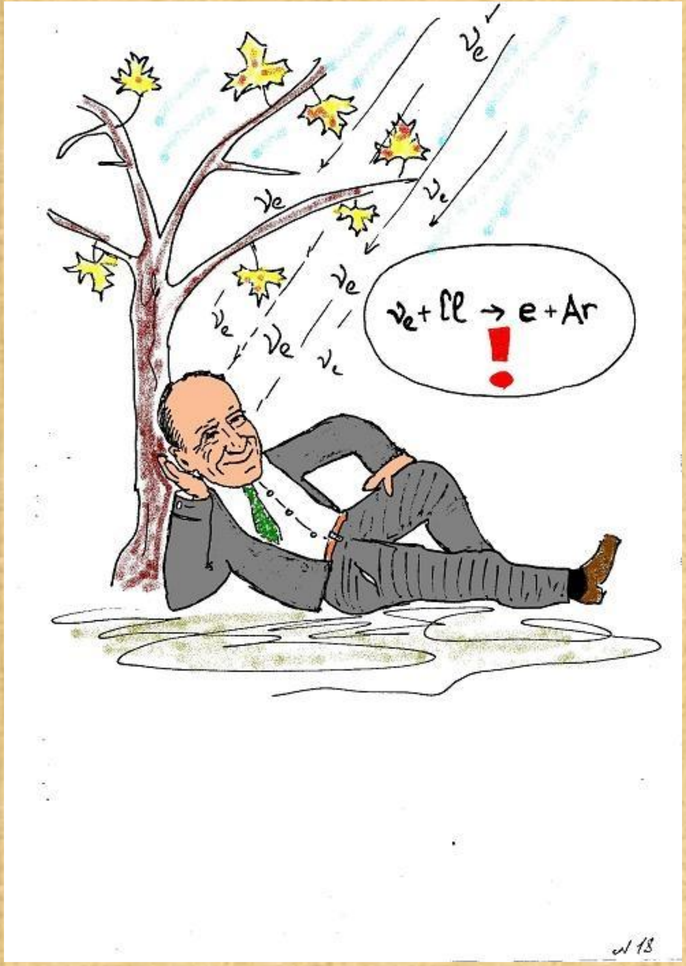

c (10^16 Km Cl^37 + ν → A^37 + e

he is evaluating in his mind the neutrino flux and the amount of Chlorine needed to detect a such elusive particle that can travel through 10^{16} Km of solid matter without interact !

At the end of 1951 Pontecorvo is seriously hoping to be able to do the Chlorine/Argon experiment.


like the classical experiment of Leipunsky) The conclusion is that such possibility is not too far from present day facilities. A short report on this subject was written

It should be very interesting to find this *"short report"* to know how and where such possibility to perform the experiment existed for him in Russia. Unfortunately this possibility didn't realize, may be simply because the access to a nuclear reactor was not allowed to him.



Dreaming to detect neutrinos from the sun !
by Misha Bilenky

Three years later, in 1954, R. Davis tried to use the Cl^{37}-Ar^{37} method in an attempt to detect reactor neutrinos exposing a 3900-liter tank of carbon tetrachloride (CCl_4) at the Brookhaven Research Reactor. And only in 1967, 21 years after the original Pontecorvo proposal, R. Davis used the Cl^{37}-Ar^{37} method to detect the neutrinos emitted by the sun, thus showing a deficit in the predicted solar neutrino flux.
In 2002 R. Davis was awarded with the Nobel Prize

$\nu_\mu \neq \nu_e$

"At the Laboratory of Nuclear Problems of JINR in 1958 a proton relativistic cyclotron was being designed with a beam energy 800 MeV and a beam current 500 A… omissis..At the beginning of 1959 I started to think about the experimental research program for such an accelerator.…omissis… (one experiment) was intended to clear up the question as to whether $\nu_e \neq \nu_\mu$." Pontecorvo writes that in "The infancy and youth of neutrino physics: some recolletions" (Journal de Physique, 1982, n.12,vol 43, C8-221), and few lines later he asserts: *"for people working on muons in the old times, the question about different types of neutrinos has always been present.*

It seems to me that what he writes at page 8 of his Notebook at the beginning of November 1950

and few lines later

reinforces the fact that Pontecorvo had always the suspicion that the two neutrinos in the muon decay were two different type of particles.

$\nu_\mu \neq \nu_e$ acknowledges the Bruno's intuition

The new powerful cyclotron foreseen at Dubna could be for Pontecorvo the good occasion to answer that question.

In the paper *"Electron and Muon Neutrino" (J.Exptl. Theoret.Phys.37 (1959) p.1751)* he writes many possible reactions induced by neutrino (or antineutrino) beams that could be forbidden if $\nu_e \neq \nu_\mu$.

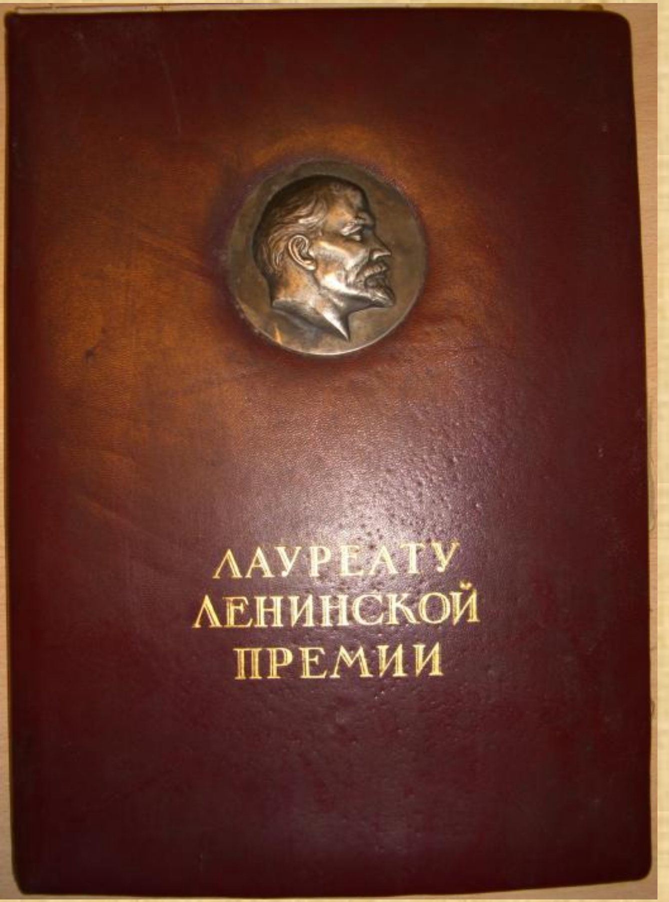
"There are no reasons for asserting that ν_e and ν_μ are identical particles" he writes just before to itemize the long list of possible interesting reactions, and continues: *" the existence of two different types of neutrinos, which are not able to annihilate, is attractive from the point of view of the symmetry and the classification of particles and might help to understand the difference in nature of muons and electrons."*

Finally, in the paper Pontecorvo proposes to use an anti- ν_μ beam to look for the reaction anti-$\nu_\mu + p \rightarrow \mu^+ + n$ and to check that the anti-$\nu_\mu + p \rightarrow e^+ + n$ is forbidden.

Unfortunately the foreseen 800 MeV cyclotron was never built at Dubna !

The experiment was done three years later at the Brookhaven AGS by G. Danby et al. (Phys. Rev. Lett. 9 (1962) 36). For the experimental proof that $\nu_e \neq \nu_\mu$, L.M.Lederman, M.Schwartz and J.Steinberger were awarded with the Nobel Prize in 1988.

Lenin Prize in 1963



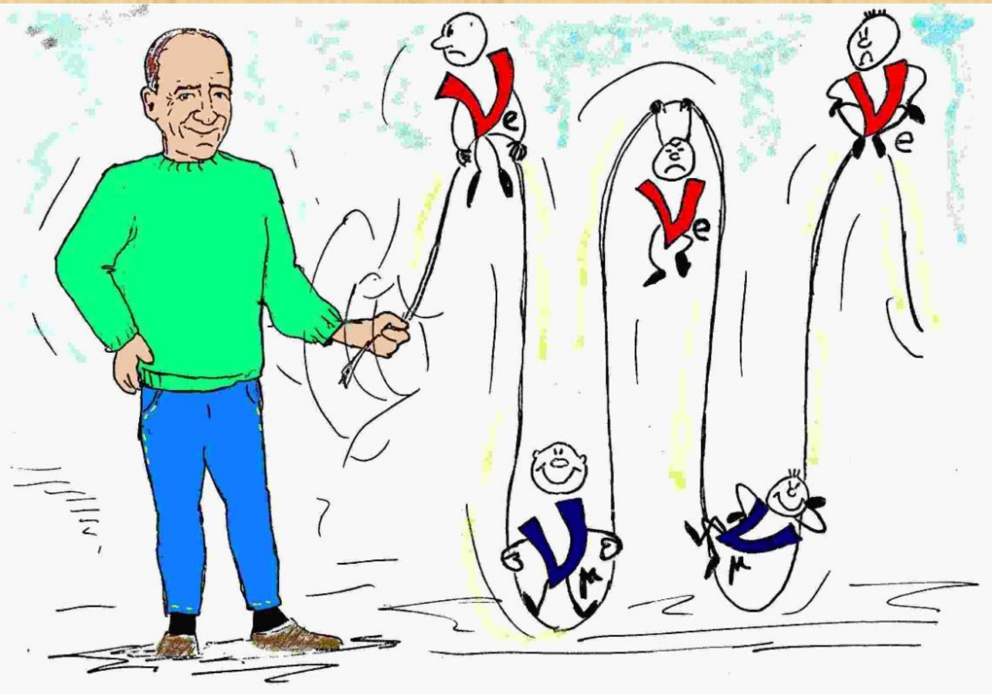
I guess that many of us would agree that Bruno Pontecorvo probably missed a couple of Nobel Prizes. The lack of enough resources and facilities (powerful accelerators, nuclear reactors, underground caverns) available to him in Russia denied to the experimental physicist Pontecorvo the possibility to realize his prophetical theoretical ideas in successful experiments. On the other hand possible collaborations of with international communities (CERN, USA, etc.) were at that time unthinkable, since he wasn't allowed to go outside the Soviet Union with the pretext of his safety ! More than that, as S.S.Gershtein affirms in the Recollections on B. Pontecorvo, *"he was not granted access to any reactor".*

Nonetheless Bruno Maximovich Pontecorvo was awarded the Lenin Prize in 1963 for his work on physics of weak interactions and neutrino physics. In 1964 he become full member of the USSR Academy of Sciences and he was awarded many of the highest USSR orders.

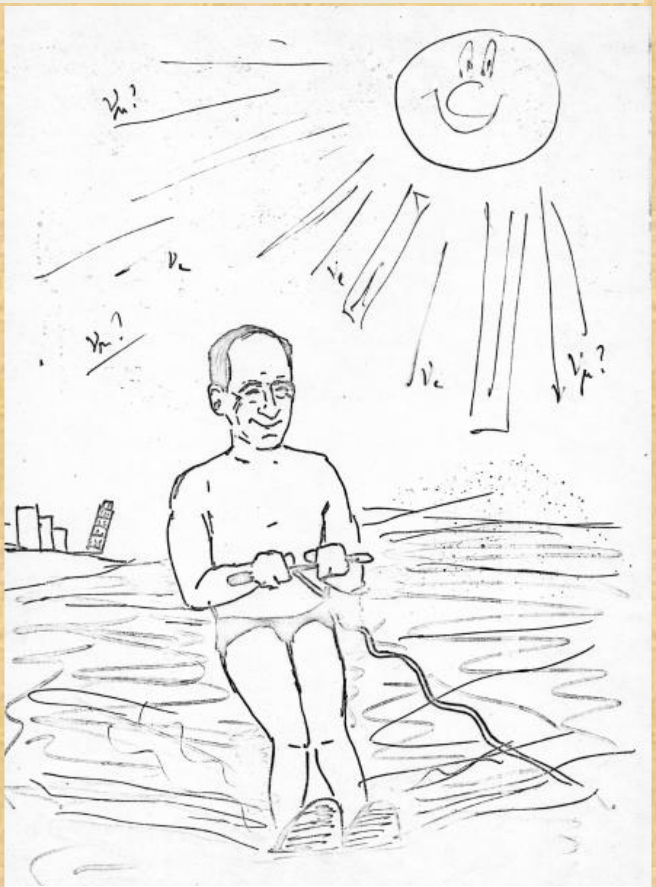
neutrino oscillations

The more revolutionary idea of Bruno Pontecorvo is certainly the *"neutrino oscillations".*
The first Bruno's intuition of this process can be found in a paper of 1957 *"Mesonium and antimesonium"* *(J.Exptl.Theoret.Phys,33,549 (1957).* He writes: *"We discuss here the problem as to whether there exist other mixed neutral particles (not necessarily elementary ones) (besides the K^0-mesons) which are not identical to the corresponding antiparticles and for which the particle-antiparticle transitions are not strictly forbidden."* and concludes *"....if the conservation law for neutrino charge took no place, neutrino-antineutrino transitions in vacuum would be in principle possible .*

I will not review the various papers that from 1957 to 1967 brought Pontecorvo to anticipate of more than ten years the phenomenon of the deficit of the solar neutrinos or to introduce the concept of sterile neutrinos, I will simply entrust to the artistic vein of Misha Bilenky the description of the phenomenon of the neutrino oscillations.



$\nu_e \leftrightarrow \nu_\mu$ as seen by Misha Bilenky



Tanning in the Sun
as seen by Misha Bilenky

neutrino oscillations

In 1969, Pontecorvo writes a paper together with V. Gribov *"Neutrino astronomy and lepton charge"* (Phys. Lett 1969, 28B,7,493-496) where they write the equations of the oscillations $\nu_e \leftrightarrow \nu_\mu$:
"It is shown that lepton nonconservation might lead to a decrease in the number of detectable solar neutrinos at the earth surface, because $\nu_e \leftrightarrow \nu_\mu$ oscillations, similar to the $K^0 \leftrightarrow$ anti-K^0 oscillations. Equations are presented describing such oscillations for the case when there exist only four neutrino states".

In this paper Gribov and Pontecorvo assume that neutrinos are particles with non-zero mass different from the other fundamental fermions. While the charged leptons and quarks are Dirac particles, the neutrinos hypothesized here are Majorana particles. The question of whether neutrinos are actually Majorana particles or not is a fundamental question which remains open and which only the detection of a neutrino-less double beta decay could solve.

In 1975 Pontecorvo writes with S.M. Bilenky the paper "Quark-lepton analogy and neutrino oscillations" (JINR Preprint E2-9383, Dubna, 1975; Phys. Lett 1976, 61B, 248.), where neutrinos are Dirac particles to which a mass is given as to all other fundamental fermions (quarks and leptons) with the standard Higgs mechanism of spontaneous symmetry breaking: *"In this note we consider neutrino mixing starting from a different point of view suggested by an analogy between leptons and quarks. We assume that each neutrino is described by a four-component spinor."*

In 1976, Pontecorvo and Bilenky publish the paper "Again on neutrino oscillations" (Lett. Nuovo Cimento, 1976, 17, 569) where they further generalize the theory of neutrino oscillations by introducing in the Lagrangian both Dirac and Majorana mass terms. The theory of neutrino oscillations thus assumed its most general form by introducing elements of possible new physics beyond the Standard Model.

Now only the experiments can give the answer to what is the real nature of neutrinos. They conclude the paper saying: *"In conclusion let us stress that the main points related to oscillation phenomena are: finite neutrino masses, neutrino mixing, lepton charge violation, number of neutrino types. Thus the questions which might be answered in experiments based on neutrino oscillation ideology directly concern the very nature of neutrinos."*

The Legacy of Bruno Pontecorvo

The conclusion of the 1976 paper, where the theory assumes its most general form by introducing in the Lagrangian both Dirac and Majorana mass terms, is the following:
"In conclusion let us stress that the main points related to oscillation phenomena are: finite neutrino masses, neutrino mixing, lepton charge violation, number of neutrino types. Thus the questions which might be answered in experiments based on neutrino oscillations ideology directly concern the very nature of neutrinos."

Once again, the theoretician Pontecorvo call for help the experimental physicist and affirms that only the experiments can now give the answer to what is the real nature of neutrinos.
This is, I guess, the Legacy of

the scientist Bruno Pontecorvo

With his revolutionary theoretical ideas he opened an impressive experimental program which continues today with more and more powerful and complex detectors that hopefully will bring us to the Physics Beyond the Standard Model. A review of this huge experimental program will be done in Pisa next 18-20 September at the "Symposium in honor of Bruno Pontecorvo for the centennial of the birth": http://www.pi.infn.it/pontecorvo100

An even more important Legacy of

the man Bruno Pontecorvo

to the future generations is what he writes in his autobiographic note of 1988 for the *"Enciclopedia della Scienza e della Tecnica"*. He acknowledges to have been very wrong and very naive in believing in political views dominated by a not logic category that he calls *"religione"* (religion) a kind of *"credo fanatico"* (fanatical belief). Nonetheless, he still strongly believes that a real democratic society *"fondata su leggi avanzate e sui diritti dell'uomo"* (based on advanced laws and on the human rights) is not an Utopia.

Pisa exhibition on Bruno Pontecorvo

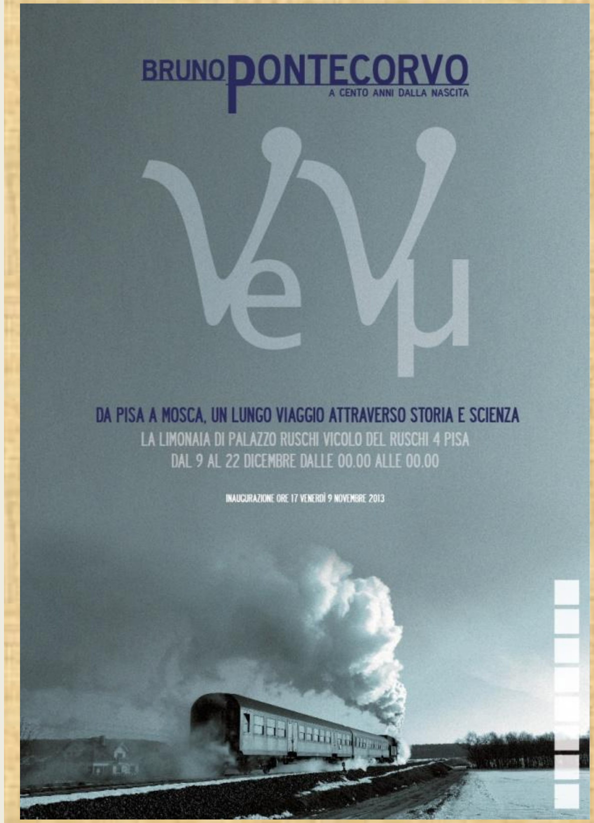
from November 9 to December 22, 2013
at “La Limonaia”, vicolo del Ruschi 4, Pisa

You are all kindly invited to this exhibition where you can find many original documents on the Bruno Pontecorvo’s life.

I would like to thanks the organizers of this exhibition and particularly V.Cavasinni, M.M.Massai, G.Spandre and E. Volterrani who gave me access to some of the documents I used to prepare this presentation.

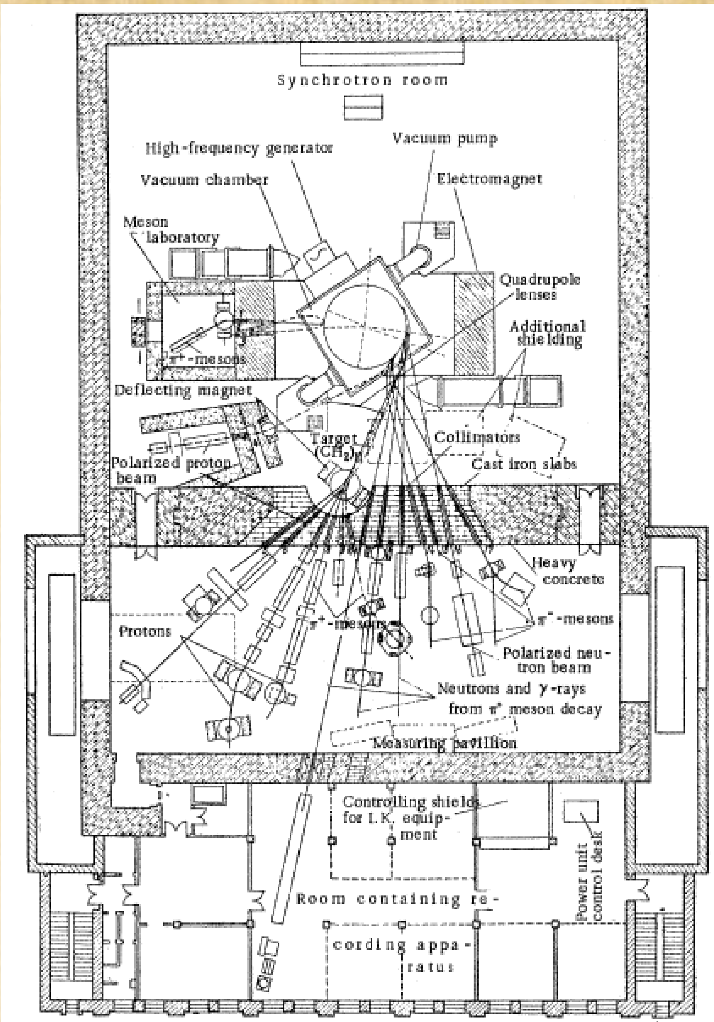
In Pisa we aim at organizing a group of people to continue studying the life and documenting the revolutionary ideas of Bruno Pontecorvo and eventually to create a permanent exhibition.

Special thanks to Gil Pontecorvo for helpful discussions and for providing us precious material for the exhibition. We wish also to thank Misha Bilenky for providing us his amusing drawings illustrating with great visual power the Bruno Pontecorvo’s intuitions.



Thanks for your attention

In the 1953 the accelerator was upgraded to a six-meter synchrocyclotron, the protons were accelerated up to 680 MeV and the proton current almost doubled. 14 beams of various kind become available (protons, neutrons, $\pi^{\pm}$, $\mu^{\pm}$, γ from π^0)



Synchrocyclotron beams

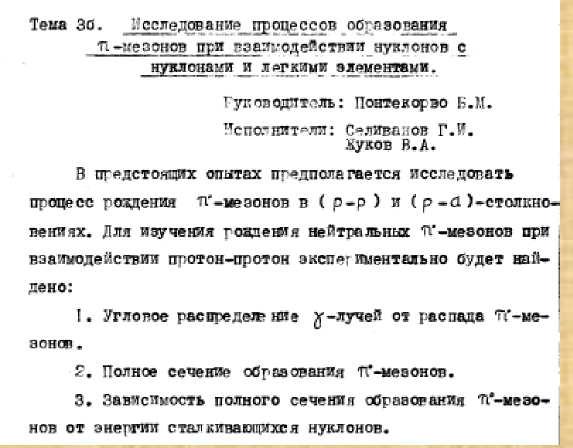
Kind of particle	Energy (MeV)	Collimator number	Beam flux $cm^{-2}\ sec^{-1}$
Protons	675 ± 6	7 as well as 6 or 8	$1{,}5 \cdot 10^9$
Polarized protons.	640 ± 10	4	$4 \cdot 10^5$
	610	6	$6 \cdot 10^5$
Neutrons	for the spectrum interval $500 \leq E_n \leq 650$	11, 12, 13	$(3 \div 4) \cdot 10^4$
Polarized neutrons	for the spectrum interval $450 \leq E_n \leq 600$	16	10^4
π^+-mesons	150	8	450
	300	8	1000
	310	9	1600
	360	8	150
π^--mesons	300	1	500
	330	1	200
	370	3	70
μ^+-mesons	90	8	$20 \div 30$
μ^--mesons	25	17	60
γ-quanta from π^0-meson decay	$10 \leq E_\gamma \leq 600$	12	$3 \cdot 10^3$

Intensities of particle beams after 1953

Internal reports on π-mesons production

The results of all experiments carried on by Bruno Maximovich Pontecorvo with his group of young researchers in the period 1951-1954 at the five-meter cyclotron were published as internal reports in russian, some of those were also published later in 1955. In these early experiments the production of single charged and neutral π mesons with proton and neutron beams on proton and complex nuclei were performed. Here there is a couple of examples:

The π meson production was extensively studied in p-p and p-d interactions *(B.M.Pontecorvo, G.I.Selivanov, V.A. Zhukov, RINP,1953)* and the results reported in this internal report in Russian.


Тема 36. Исследование процессов образования π-мезонов при взаимодействии нуклонов с нуклонами и легкими элементами.

Руководитель: Понтекорво Б.М.

Исполнители: Селиванов Г.И.
Жуков В.А.

В предстоящих опытах предполагается исследовать процесс рождения π⁺-мезонов в (p-p) и (p-d)-столкновениях. Для изучения рождения нейтральных π°-мезонов при взаимодействии протон-протон экспериментально будет найдено:

1. Угловое распределение γ-лучей от распада π°-мезонов.

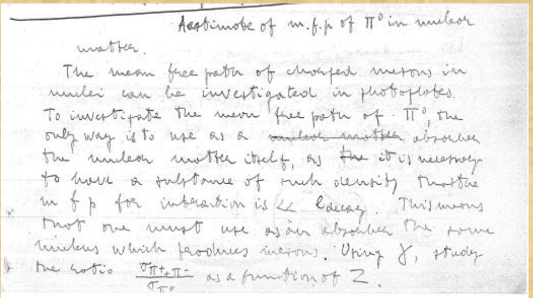
2. Полное сечение образования π°-мезонов.

3. Зависимость полного сечения образования π°-мезонов от энергии сталкивающихся нуклонов.

Theme 36. Study of the π meson production in nucleon-nucleon and nucleon-light nuclei collisions

Leader: Pontecorvo B.M.
Executors: Selivanov G.I.
Zhukov V.A.

The π^0 production in nuclei of different atomic weight allowed the measurement of the π^0 mean free path in nuclear matter *(B.M.Pontecorvo, G.I. Selivanov, RINP,1952; Dokl.Acad.Nauk SSSR,102,495 (1955))* following the idea that Pontecorvo wrote in the first pages of his Notebook as soon as he arrived in Dubna in November 1950.


m.f.p of π⁰ in nuclear matter.

The mean free path of charged mesons in nuclei can be investigated in photoplates. To investigate the mean free path of π⁰, the only way is to use as a ~~nuclear matter~~ absorber the nuclear matter itself, as ~~the~~ it is necessary to have a substance of such density that the m f p for interaction is ≪ l_{decay}. This means that one must use as an absorber the same nucleus which produces mesons. Using γ, study the ratio $\frac{\sigma_{\pi^+ + \pi^-}}{\sigma_{\pi^0}}$ as a function of Z.

In 1953 the accelerator was upgraded to a six-meter cyclotron, the protons were accelerated up to 680 MeV and the proton current almost doubled. Some of the previous experiments were done once again at this higher energies by the Pontecorvo's group *(Yu.D.Balashov,V.A.Zhukov, B.M.Pontecorvo, G.I.Selivanov, RINP,1955)*. In 1954 As soon as well-collimated π-meson beams became available at the cyclotron, several measurements were performed by the Pontecorvo's group on the energy dependence of the total cross sections for π mesons on hydrogen, deuterium and on complex nuclei. See *"The Soviet Journal of Atomic Energy 1957,vol.3,5,1273-1314"* for a review.

Scattering of π-mesons on hydrogen, deuteron and complex nuclei

As soon as well-collimated π-meson beams became available at the cyclotron in 1954, Pontecorvo became very interested in doing experiments of π-meson scattering on protons and complex nuclei. In a review paper with V.P.Dzhelepov on the experiments performed with the cyclotron in ***"The Soviet Journal of Atomic Energy 1957, vol.3, 5, 1273-1314"***, he writes:

"the interaction between charged particles takes place through photons, which are the quanta of the electromagnetic field. Therefore, the properties of photons are strongly related to the characteristics of the electromagnetic forces between charged particles. Similarly, the properties of π-mesons are intimately related to the forces between nuclei, which means that they are related to nuclear forces. Meson theory is based on the hypothesis, first formulated by Yukawa, that nuclear forces are caused by mesons. Although this concept is correct, meson theory is still, unfortunately, in the early stages of its development."

Several measurements were performed by the Pontecorvo's group on the energy dependence of the total cross sections for π mesons on hydrogen and deuterium. ***(A.E.Ignatenko,A.I.Mukhin,E.B. Ozerov,B.M.Pontecorvo; Dokl.Acad. Nauk SSSR,103,45(1955); Dokl. Acad.Nauk SSSR,103,209(1955); J.Exptl.Theoret.Phys (USSR) 30,7 (1956). A.I.Mukhin,E.B.Ozerov,B.M. Pontecorvo;J.Exptl. Theoret.Phys (USSR) 31,371 (1956)).*** See for instance the up-right figure. From its caption one reads:

"The "resonance" behaviour of the cross sections is in the vicinity of 190 MeV characterizes the meson-nucleon interaction in state with isotopic spin and total angular momenta 3/2".

Measurements of total cross section of π mesons on complex nuclei were also performed by the Pontecorvo's group. ***(A.E.Ignatenko,A.I.Mukhin, E.B. Ozerov,B.M.Pontecorvo; Dokl.Acad. Nauk SSSR,103,395(1955); J.Exptl. Theoret.Phys (USSR) 31,545 (1956)).*** See for instance the down-right figure. From its caption one reads:

"The curves are reminiscent of the energy dependence of the cross section for the total interaction of π^+ and π^- mesons with nucleons. Analysis shows that the interaction of π-mesons with nuclei takes place primarily by means of interactions with individual nucleons of the nucleus.

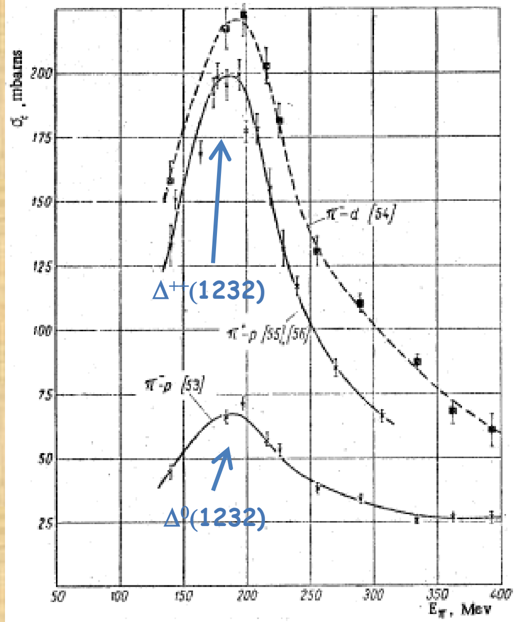


Fig. 12. Total cross section for the interaction of π^+- and π^--mesons with hydrogen and deuterium. The "resonance" behavior of the cross sections is in the vicinity of 190 Mev characterizes the meson-nucleon interaction in the state with isotopic spin and total angular momenta 3/2. At an energy of $E_{lab} \geq 300$ Mev the contribution to scattering from the state with isotopic spin 1/2 becomes significant.

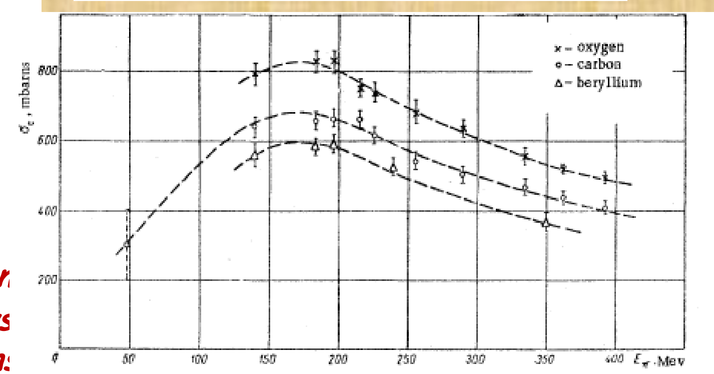


Fig. 15. The energy dependence of the total cross section for the interaction of π-mesons with light nuclei [65]. The curves are reminiscent of the energy dependence of the cross section for the total interaction of π^+- and π^--mesons with nucleons. Analysis shows [66] that the interaction of π-mesons with nuclei takes place primarily by means of interactions with individual nucleons of the nucleus.

Scattering of π mesons on hydrogen

On the review paper written together with V.P.Dzhelepov in ***"The Soviet Journal of Atomic Energy 1957,vol.3, 5,1273"*** *one can read: "Several experiments (**see for instance A.I.Mukhin,E.B.Ozerov, B.M.Pontecorvo; J.Exptl.Theoret.Phys (USSR) 31,371 (1956).A.I.Mukhin,B.M.Pontecorvo;J.Exptl.Theoret.Phys (USSR) 31,550 (1956)**) were devoted..omissis..to investigations of angular distributions of π-mesons scattered by hydrogen in the $\pi^+ + p \rightarrow \pi^+ + p$, $\pi^- + p \rightarrow \pi^- + p$, $\pi^- + p \rightarrow \pi^0 + n$ reactions for the following meson energies: 176, 200, 240, 270 MeV. Some of the data obtained is shown in Figs. 13 and 14. All data obtained, in particular the equality of the cross section for the interaction of both π^+ and π^- mesons with deuterium, verifies the principle of charge symmetry for a set of mesons and nucleons, as well as the more rigorous principle of charge independance..omissis..Experiments verified the fact that in the energy range up to 300 MeV the meson-nucleon interaction is extremely strong for the state whose isotopic spin and total angular momentum are 3/2. The scattering cross section in this state attains its maximum possible value at a π meson energy of about 190 MeV. It is therefore often said that the meson-nucleon interaction has a "resonant" character(*). It is possible that this resonance is related to the nucleon structure, although one may not assert this at present..omissis.. The high accuracy with which the angular distribution of the π^+-meson scattering by hydrogen have been measured for energies higher than 200 MeV allowed the first phase analysis accounting not only for the s- and p-states, but also for the d-state. It follows from this analysis that the meson-nucleon interaction radious is about 7×10^{-14} cm.*

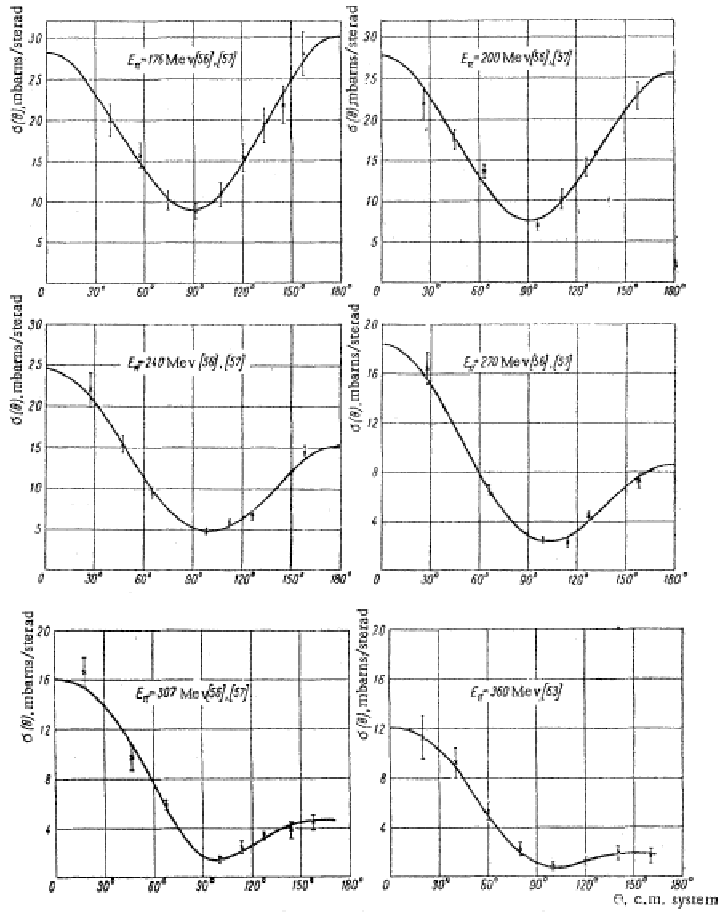


Fig. 13. The angular distribution of π^+-mesons elastically scattered by hydrogen for various energies. It is seen from the figure that close to the "resonance" energy (190 Mev) the angular distribution is symmetric about 90°. At energies greater than the "resonance" energy, forward scattering predominates.

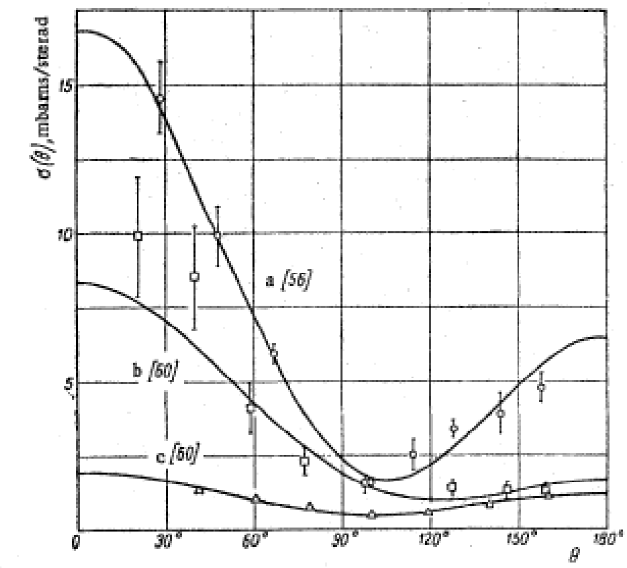


Fig. 14. Scattering of π-mesons by hydrogen at 307 Mev in the following processes: a) $\pi^+ + p \rightarrow \pi^+ + p$; b) $\pi^- + p \rightarrow \pi^0 + n \rightarrow \gamma + \gamma + n$; c) $\pi^- + p \rightarrow \pi^- + p$. From the data given in this figure and in Fig. 13, one can obtain the coupling constant f^2 of the meson-nucleon interaction, which is found to be about 0.1.

(*) *the* Δ(1232)

Strange Particles

Since the end of 1950 Pontecorvo (as we saw from his notebook and from the previous internal report) was deeply convinced that the only way to solve the contradiction posed by particles which are strongly produced but are decaying weakly is to assume that they must be produced in pair. **In 1953, from an experimental point of view, this fact was not completely clear**; on the contrary this hypothesis was in contradiction with the results of the experiment of Schein et al. ***(Schein M.,Haskin D.,Glasse R.,Fainberg F.,Brown K.;Congress International sur le rayonement cosmique, Bagnere de Bigorre, 1953).*** This experiment was claiming that five events with Λ^0–particles from π^- mesons on carbon were observed on photographic plates and that was in contradiction with the experiment of Garwin **(Garwin R.L.;Phys.Rev.,1953,vol.90,p.274)** who was finding un upper-limit of $\sigma \leq 7*10^{-32}$ cm^2 to the cross section per nucleon for the production of Λ^0 by 450-MeV protons on carbon .

As usual, the theoretical physicist Pontecorvo, as brilliant experimenter, decides to clarify this point by himself with an experiment trying to observe the formation of Λ^0–particles in collisions of 670 MeV protons with carbon nuclei.***(Baladin M.P.,Balashov B.D.,Zhukov V.A.,Pontecorvo B.M.,Selivanov G.I. Report of the Inst.for Nuclear Problem,Acad.Sci. USSR,1954.).*** The experiment was looking , as done by Garwin, for Λ^0–particles in the decay channel $\Lambda^0 \to$n+π^0. Gamma rays from the decay of π^0 mesons were detected by means of a telescope of scintillation and Cherenkov counters. It was found un upper limit for the **cross section for production of Λ^0–particles in the reaction Nucleon+Nucleon$\to\Lambda^0$ + Nucleon of $\sigma \leq 10^{-31}$cm^2/nucleon.** Therefore conclusion was reached that:

> ***"The small value of the cross section for the formation of Λ^0 particles in the interaction of protons with an energy of 670 MeV with complex nuclei agrees with the hypothesis of the fundamental transformation of a nucleon according to the scheme (N) $\leftrightarrow$ (Λ^0) + (heavy meson)."***

The production in pair of V-particles and heavy mesons according to the previous scheme, hypothesized by Pontecorvo already in the 1951, was then observed in π^-p collision with π^- of 1.5 BeV from the BNL Cosmotron by W.B.Fowler et al. *(Phys. Rev. 93, 861 (1954))*

PHYSICAL REVIEW   VOLUME 93, NUMBER 4   FEBRUARY 15, 1954

Production of Heavy Unstable Particles by Negative Pions*

W. B. Fowler, R. P. Shutt, A. M. Thorndike, and W. L. Whittemore
Brookhaven National Laboratory, Upton, New York

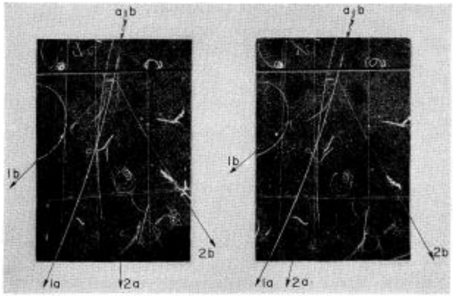


Fig. 1. Case C. Diffusion cloud-chamber photograph of two neutral V particles (a) and (b), whose lines of flight are almost colinear. (a) is believed to be a Λ^0 decaying into a proton (1a) and a negative π meson (2a). Tracks 1a and 2a practically coincide in the right view. (b) is probably a ϑ^0 decaying into π^+ (1b) and π^- (2b).

π^-+p $\to\Lambda^0$+K$^0\to$p π^-+π^+ π^-

first event observed in a cloud chamber by Fowler et al.

These important contributions given by Pontecorvo to the problem of understanding the properties of the "strange particles" are not often acknowledged to him by the scientific community.
He was probably the first to have the intuition that the contradictory behavior of these strange particles can be explained if are produced in pair. Unfortunately this idea remained hidden in internal reports written in Russian, not accessible for long time to the vast community of physicists outside the Soviet Union.

Free neutrino detection

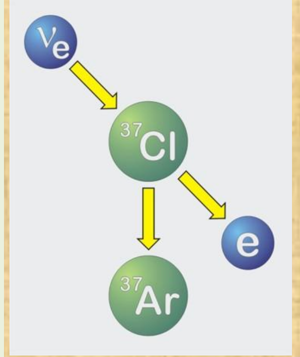
At the end of 1951, when Pontecorvo writes this page in his Notebook, he is evidently thinking to the brilliant method that he proposed in its famous publication "Inverse beta process" (Chalk River Report, PD-205, 1946) to detect "free neutrinos".
At that time it was believed that the direct detection of neutrinos, because of his negligible cross section with matter as evaluated by Bethe and Peierls ($\sigma < 10^{-44}$ cm ^{2}, corresponding to a penetrating power of more than 10^{16} Km in solid matter), was "absolutely impossible".

In the paper of '46, proposing his method to directly detect "free neutrinos", Pontecorvo asserts:

"it is true that the actual β transition involved, i.e., the actual emission of a β particle in process $\nu + Z \rightarrow \beta^{-} (\beta^{+}) + Z \pm 1$ ..omissis..is certainly not detectable in practice.",

but immediately 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 know..omissis…The essential point, in this method, is that radioactive atoms produced by an inverse β-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."



Then Pontecorvo proposes, as the best candidate, the use of the reaction $\nu + {}^{37}Cl \rightarrow \beta^{-} + {}^{37}Ar$

"irradiating with neutrinos a large volume of Clorine or Carbon Tetra-chloride, for a time of the order of one month, and extracting the radioactive ^{37}Ar from such volume by boiling. The radioactive argon would be introduced inside a small counter; the counting efficiency is close to 100%, because of the high Auger electron yield."

The choice of this elements was done *"according to a compromise between their desirable properties…"*, namely 1) The material irradiated must not be to much expensive, since large volume is needed. 2) The nucleus radioactive produced should have a rather long decay period because of the long time needed for the separation. 3) The separation of the radioactive atoms must be relatively simple. 4) The difference in mass of the elements Z and Z+1 must be small because the inverse β process cross section increases with the energy. 5) The background of Z+1 element produced by other causes must be as small as possible.

The sources proposed by Pontecorvo for an "inverse beta process" experiment is the neutrino flux from the sun (*"the neutrino emitted by the sun, however, are not very energetic"*) or the high intensity neutrino source from a pile of a nuclear reactor (*"the neutrino source is the pile itself, during operation. In this case, neutrinos must be utilized beyond the usual pile shield. The advantage of such an arrangement* (with respect to use as source of hot uranium metal extracted from a pile) *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"*).

Free neutrino detection

The first idea of Pontecorvo to detect "free neutrinos" was to use the "inverse beta process" in the reaction:

$$\nu + {}^{35}_{17}Cl \rightarrow \beta^{+} + {}^{35}_{16}S$$

(Chalk River Report, PD-141,25 May, 1945):

"The ${}^{35}_{16}S$ is a β–active radioelement, decaying to ${}^{35}_{17}Cl$ with a period of 87.1 days the energy of the β–ray radiation being only 120 KeV. ${}^{35}_{16}S$ would be produced by absorption of a neutrino and emission of a positive electron from the original ${}^{35}_{17}Cl$".

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 conditions indicated in the preceding paragraph. According to Seaborg's Table of Isotopes(4), ${}^{35}_{16}S$ is a β-active radioelement, decaying to ${}^{35}_{17}Cl$ with a period of 87.1 days, the energy of the β-ray radiation being only 120 kv. ${}^{35}_{16}S$ would be produced by absorption of a neutrino and emission of a positive electron from the original ${}^{35}_{17}Cl$. According to

In the years '45-46 the difference between neutrino and antineutrino was not very clear and the Chlorine-35/Sulphur-35 reaction could only be used to detect reactor neutrinos (i.e. antineutrinos), while the Chlorine-37/Argon-37 reaction could be used to look for solar neutrinos.

However in 1948, as can be seen from this letter of T. Turkevich to Pontecorvo, there was already the suspicion that reactor (anti) neutrinos could not induce the Chlorine/ Argon process and in the letter we read: *"The above may not be right, and in any case gives only new incentive to doing your experiment".*

The idea of a Chlorine/Argon experiment was not pursued when Pontecorvo moved from Chalk River to England, although some tests were already done to detect the 2.8 KeV Auger electrons in Argon-37 using proportional counters with high amplification (D.H.W. Kirkwood, B.Pontecorvo, G.C.Hanna, Phys.Rev.74(1948)497

July 26, 1948

Dr. Bruno Pontecorvo
~~Chalk River~~ Laboratory
Chalk River, Ontario, Canada

Dear Ponte,

...omissis...

not. As I understand it, if it does, there is a "real" difference between a neutrino and an "anti-neutrino". In this case I wonder if the pile (β⁻decays) which furnishes "anti-neutrinos" can induce a process such as Cl^{37} (ν, e^-) A^{37} which really requires "neutrinos". (See also abstract T-1, Washington meeting, on "double beta decay").

The above may not be right, and in any case gives only new incentive to doing your experiment, but I pass it on to indicate the obvious interest in the work.

Unfortunately I don't remember your schedule well enough, but I still hope that you will be able to visit us in Chicago before leaving for England and that we will be able to talk and play some tennis.

With best regards and thanks again,

Tony Turkevich

Tony Turkevich

Free neutrino detection

In **1954**, R. Davis tried to use the Cl^{37}-Ar^{37} method in an attempt to detect reactor neutrinos exposing a 3900-liter tank of carbon tetrachloride (CCl_4) at the Brookhaven Research Reactor.

PHYSICAL REVIEW VOLUME 97, NUMBER 3 FEBRUARY 1, 1955

Attempt to Detect the Antineutrinos from a Nuclear Reactor by the $Cl^{37}(\bar{\nu},e^-)A^{37}$ Reaction*

RAYMOND DAVIS, JR.
Department of Chemistry, Brookhaven National Laboratory, Upton, Long Island, New York
(Received September 21, 1954)

The antineutrino source of the Brookhaven reactor was not powerful enough to detect any possible signal with the target volume of CCl_4 exposed and so no signal was observed. Therefore Davis moved the experiment to the Savannah River reactor, which was the most intense antineutrino sources in the world at that time. Similarly no reactor neutrinos was found even when the experiment was upgraded to a 11.400-liter CCl_4 target (Davis R.Jr., "An attempt to observe the capture of reactor neutrinos in Chlorine-37". UNESCO Conf., Paris, Vol.1, 728, 1958). This was the first evidence that antineutrinos (reactor neutrinos) are different particles from neutrinos.

Meanwhile, in **1953**, F. Reines and C.L.Cowan Jr. tried a first attempt to detect free reactor neutrinos at the Hanford nuclear reactor in the reaction antineutrino + proton → neutron + positron by using liquid scintillators. The background from cosmic rays prevents to draw a definitive conclusion on this experiment. Only several years later, in **1960**, after having repeated the experiment at the Savannah River reactor they could reach a definitive conclusion on the observation of free antineutinos. This discovery was recognized with the Nobel Prize to F. Reines in 1995.

Detection of the Free Neutrino*

F. REINES AND C. L. COWAN, JR.
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received July 9, 1953; revised manuscript received September 14, 1953)

PHYSICAL REVIEW VOLUME 117, NUMBER 1 JANUARY 1, 1960

Detection of the Free Antineutrino*

F. REINES,† C. L. COWAN, JR.,‡ F. B. HARRISON, A. D. MCGUIRE, AND H. W. KRUSE
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico
(Received July 27, 1959)

The other possible source of neutrinos suggested by Pontecorvo in **1946** was "*the neutrino emitted by the sun, however, are not very energetic.*" In the **1964** R. Davis, ten years after he tried to detect reactor neutrinos, in the paper Phys. Rev. Lett. 12, 303-305 (1964) proposes an experiment to detect solar neutrinos arguing that the neutrino flux from Boron-8 decay, according to J. N. Bahcall (Phys. Rev. Lett. 12, 300-302 (1964)) could be detectable.

The detector, a 378.000-liter tank of C_2Cl_4 located in the Homestake mine in South Dakota, in **1967** was operational and already from the beginning the data, published in **1968**, showed a deficit in the predicted solar neutrino flux:

the solar neutrino problem was born.

R. Davis was awarded with the Nobel Prize in 2002

VOLUME 12, NUMBER 11 PHYSICAL REVIEW LETTERS 16 MARCH 1964

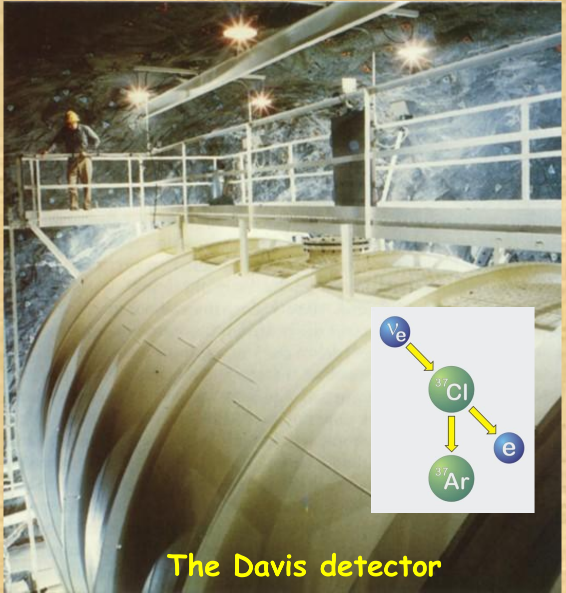
SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

VOLUME 20, NUMBER 21 PHYSICAL REVIEW LETTERS 20 MAY 1968

SEARCH FOR NEUTRINOS FROM THE SUN*

Raymond Davis, Jr., Don S. Harmer,† and Kenneth C. Hoffman
Brookhaven National Laboratory, Upton, New York 11973
(Received 16 April 1968)



The Davis detector

$\nu_\mu \neq \nu_e$

"At the Laboratory of Nuclear Problems of JINR in 1958 a proton relativistic cyclotron was being designed with a beam energy 800 MeV and a beam current 500 A. By the way, this accelerator eventually was not built. Anyway at the beginning of 1959 I started to think about the experimental research program for such an accelerator. First, it occurred to me that neutrino investigations at accelerator facilities are perfectly feasible and that an healthy and relatively cheap neutrino program could be accomplished by dumping the proton beam in a large Fe block. …omissis… (one experiment) was intended to clear up the question as to whether $\nu_e \neq \nu_\mu$." Pontecorvo writes that in "The infancy and youth of neutrino physics: some recolletions" Journal de Physique, 1982, n.12,vol 43, C8-221. And then he continues: *"I have to come back a long way (1947-1950). Several groups, among which J. Steinberger, E. Hincks and I, and others were investigating the (cosmic) muon decay. …omissis… the decaying muon emits 3 particles: one electron and two neutral particles, which were called by various people in different way: two neutrinos, neutrino and neutretto, ν and ν', etc. I am saying this to make clear that for people working on muons in the old times, the question about different types of neutrinos has always been present.*

$\nu_\mu \neq \nu_e$ acknowledges the Bruno's intuition

It seems to me that what he writes at page 8 of his Notebook at the beginning of November 1950

and few lines later

reinforces the fact that Pontecorvo had always the suspicion that the two neutrinos in the muon decay were two different type of particles.

The new powerful cyclotron foreseen at Dubna could be for Pontecorvo the good occasion to answer that question. In the paper *"Electron and Muon Neutrino" (J.Exptl. Theoret.Phys.37 (1959) p.1751)* he writes many possible reactions induced by neutrino (or antineutrino) beams that could be forbidden if $\nu_e \neq \nu_\mu$. *"There are no reasons for asserting that ν_e and ν_μ are identical particles"* he writes just before to itemize the long list of possible interesting reactions, and continues giving some reasons (like the absence of the $\mu \to e+\gamma$ decay) for which the hypothesis of $\nu_e \neq \nu_\mu$ is attractive and concludes *" the existence of two different types of neutrinos, which are not able to annihilate, is attractive from the point of view of the symmetry and the classification of particles and might help to understand the difference in nature of muons and electrons."*
Finally, in the paper Pontecorvo proposes to use an anti- ν_μ beam to look for the reaction anti-$\nu_\mu + p \to \mu^+ + n$ and to check if the anti-$\nu_\mu + p \to e^+ + n$ is forbidden.

Unfortunately the foreseen 800 MeV cyclotron was never built at Dubna !

The experiment was done three years later at the Brookhaven AGS by G. Danby et al. (Phys. Rev. Lett. 9 (1962) 36). For the experimental proof that $\nu_e \neq \nu_\mu$, L.M.Lederman, M.Schwartz and J.Steinberger were awarded with the Nobel Prize in 1988.

neutrino oscillations - 1

The more revolutionary idea of Bruno Pontecorvo is certainly the *"neutrino oscillations"*. The first Bruno's intuition of this process can be found in a paper of 1957 *"Mesonium and antimesonium"* *(J.Exptl.Theoret.Phys,33,549 (1957)*. He writes: *"We discuss here the problem as to whether there exist other mixed neutral particles (not necessarily elementary ones) (besides the K^0-mesons) which are not identical to the corresponding antiparticles and for which the particle-antiparticle transitions are not strictly forbidden."* and concludes *"....if the conservation law for neutrino charge took no place, neutrino-antineutrino transitions in vacuum would be in principle possible .*

The following year, in 1958, when Bruno hears a false rumor that Davis has observed some events of antineutrinos produced by the Savannah River reactor, he publishes the article *"Inverse beta processes and non-conservation of lepton charge"* (*J.Exptl.Theoret.Phys,34,247(1958)*) in which he discusses in detail whether it is possible the transition neutrino-antineutrino as he had suggested in his previous article. In the paper Pontecorvo makes the hypothesis that *"a) the neutrino and antineutrino are not identical particles; b) the neutrino charge is not strictly conserved."* from which he concludes that:*" neutrinos in vacuum can transform themselves into antineutrinos and vice versa. This means that neutrino and antineutrino are particle mixtures, i.e. symmetrical and antisymmetrical combination of two truly neutral Majorana particles v_1 and v_2".*

Immediately after he adds that these assumptions may not be true, but the discussion is still interesting because they have consequences (as possible neutrino oscillations) that can be tested experimentally by the two experiments of Reines and of Cowan and Davis:

"So, for example, a beam of neutral leptons from a reactor which at first consists mainly of antineutrinos will change its composition and at a certain distance R from the reactor will be composed of neutrino and antineutrino in equal quantities."

However, he warns that such an effect could be unobsevable in these experiments because the distance between the detector and the source of antineutrinos is too small compared to the large values of R,…but: *"...it will certainly occur, at least, on an astronomic scale"*, anticipating of more than ten years, the phenomenon of the deficit of solar neutrinos.

neutrino oscillations - 2

In his famous paper of 1967 *"Neutrino experiments and the question of leptonic-charge conservation" (J.Exptl. Theoret. Phys. 53, 1717 (1967)* Bruno Pontecorvo discusses in detail the possibility of oscillations both for neutrinos (ν_e and ν_μ) in their respective antineutrinos ($\nu_{e\ (\mu)} \leftrightarrow$ anti-$\nu_{e\ (\mu)}$) and for neutrinos *e* in neutrinos μ ($\nu_e \leftrightarrow \nu_\mu$):
"If the lepton charge is not an exactly conserved quantum number, and the neutrino mass is different from zero, oscillation similar to those in K^0 beams become possible in neutrino beams."

At first he considers the neutrino oscillation with the respective antineutrinos, as he had suggested in its first article of 1957, now introducing the concept of neutrino "sterile": *"If there are two different additive lepton charges, the transitions $\nu_e \leftrightarrow$ anti-ν_e and $\nu_\mu \leftrightarrow$anti-ν_μ transform potentially "active" particles into particles, which, from the point of view of ordinary weak processes, are sterile, i.e. practically undetectable, inasmuch as they have "wrong" spirality. In such a case the only way of observing the effects in question consists in measuring the intensity and the time variation of the intensity of original active particles, but not in detecting the appearance of the corresponding (sterile) antiparticles.*

by Misha Bilenky

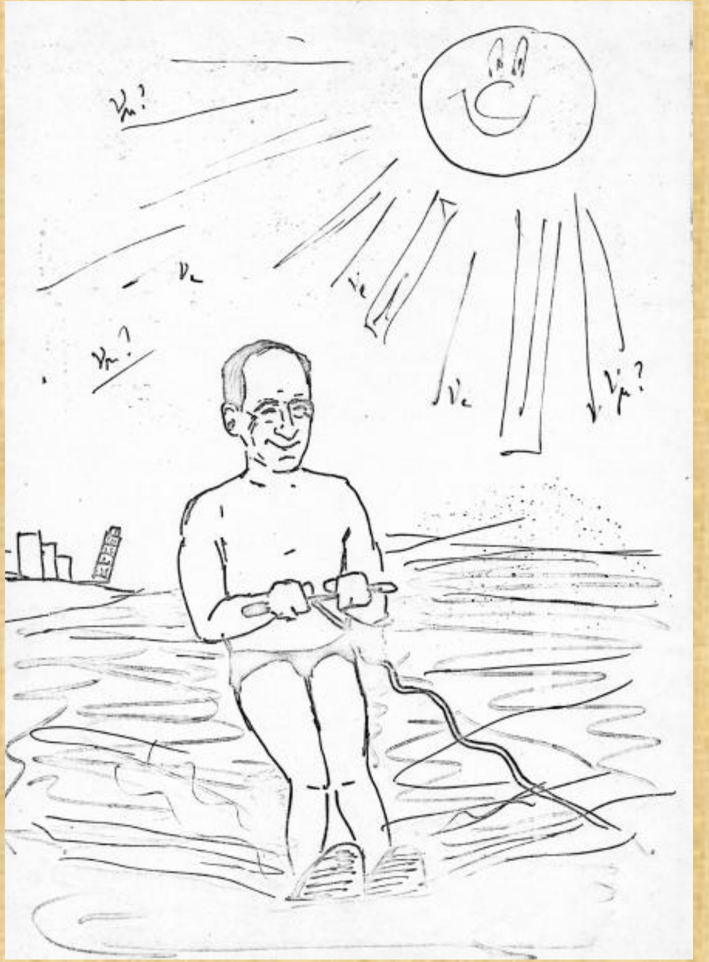
In the 1967, when the existence of two kind of neutrinos had been experimentally well proved, it is natural for him to consider also the possibility of oscillation of ν_e in ν_μ :
"Returning to the usual notations, there will take place oscillations $\nu_e \leftrightarrow \nu_\mu$, which, in principle are detectable not only by measuring the intensity and the time variation of the intensity of original particles, but also by observing the "appearance" of new particles."

neutrino oscillations - 3

The deep conviction of Pontercorvo that neutrinos have non-zero mass, although small, and are therefore susceptible to oscillations as in the system as K^0-antiK^0, derived from the intuition of a profound symmetry between leptons and hadrons at least with respect to the weak interaction, as well as for the same argument of symmetry he was convinced that the neutrino in the decay of the pion into muon + neutrino was of a different nature from the neutrino of the β decay.

Furthermore, in the paper of 1967 ***"Neutrino experiments and the question of leptonic-charge conservation"*** *(J.Exptl. Theoret. Phys. 53, 1717 (1967)* Bruno Pontecorvo observes, as already anticipated in the 1957 paper, that the best way to detect the neutrino oscillation is the measurement of the solar neutrino flux on the earth: *"From an observational point of view the ideal object is the sun."* and he quantifies it: *"The only effect on the earth's surface would be that the flux of observable sun neutrinos must be two times smaller than the total (active and sterile) neutrino flux."*

It must be noticed that at the time when Pontecorvo is writing these observations the Davis' experiment had not yet produced any result and only later this experiment really showed the existence of a deficit in the solar neutrino flux.



by Misha Bilenky

neutrino oscillations - 4

Two years later, in 1969, Pontecorvo writes a paper together with V. Gribov *"Neutrino astronomy and lepton charge"* (Phys. Lett 1969, 28B,7,493-496) where they write the equations of the oscillations $\nu_e \leftrightarrow \nu_\mu$ in the case of non-conservation of the lepton charge (lepton number) and the existence of only two Majorana neutrinos with mass different from zero:

"It is shown that lepton nonconservation might lead to a decrease in the number of detectable solar neutrinos at the earth surface, because $\nu_e \leftrightarrow \nu_\mu$ oscillations, similar to the $K^0 \leftrightarrow$ anti-K^0 oscillations. Equations are presented describing such oscillations for the case when there exist only four neutrino states".

In this paper Gribov and Pontecorvo assume that neutrinos are particles with non-zero mass different from the other fundamental fermions. While the charged leptons and quarks are Dirac particles, the neutrinos hypothesized here are Majorana particles. The question of whether neutrinos are actually Majorana particles or not is a fundamental question which remains open and which only the detection of a neutrino-less double beta decay could solve.

In 1975 Pontecorvo writes with S.M. Bilenky the paper "Quark-lepton analogy and neutrino oscillations" (JINR Preprint E2-9383, Dubna, 1975; Phys. Lett 1976, 61B, 248.), where in analogy with the mechanism of the quark mixing model (Cabibbo-GIM), neutrinos are Dirac particles to which a mass is given as to all other fundamental fermions (quarks and leptons) with the standard Higgs mechanism of spontaneous symmetry breaking: *"In this note we consider neutrino mixing starting from a different point of view suggested by an analogy between leptons and quarks. We assume that each neutrino is described by a four-component spinor."*

The following year, in 1976, Pontecorvo and Bilenky publish the paper "Again on neutrino oscillations" (Lett. Nuovo Cimento, 1976, 17, 569) where they further generalize the theory of neutrino oscillations by introducing in the Lagrangian both Dirac and Majorana mass terms. The theory of neutrino oscillations thus assumed its most general form by introducing elements of possible new physics beyond the Standard Model.

Now only the experiments can give the answer to what is the real nature of neutrinos. They conclude the paper saying: *"In conclusion let us stress that the main points related to oscillation phenomena are: finite neutrino masses, neutrino mixing, lepton charge violation, number of neutrino types. Thus the questions which might be answered in experiments based on neutrino oscillation ideology directly concern the very nature of neutrinos."*

H4 experiment

H^4 experiment

The recoil of the α particle in the $H^4 \to He^4 + \beta + \nu$ (20 MeV) is ≈ 50 kV. This is detectable in a proportional counter.

Apparatus

Apparatus for ~~the determination of~~ a search for a stable state of H^4. (Rent & Uray)

~~An expe~~ ~~The Experiment~~

~~The principle of the~~

If there is a state of H^4 stable versus emission of heavy particles, this hypothetical state must be radioactive with emission of β particles of high energy. The experiments planned is somewhat designed to find a period of this state H^4 in the millisecond region, with emission of β particles of ≈ 20 MeV. The apparatus capable of detecting β particles consists of 3 counters in coincidence.

H^4 experiment

5

Possible method of detection –

a) One irradiates a solution scintillating, and one sees delayed pulses to measure > 20 MeV.

This principle is good for:

- H4 etc
- $\pi^+ - e^+$
- $\pi^- - e^-$ when lifetime reasonable

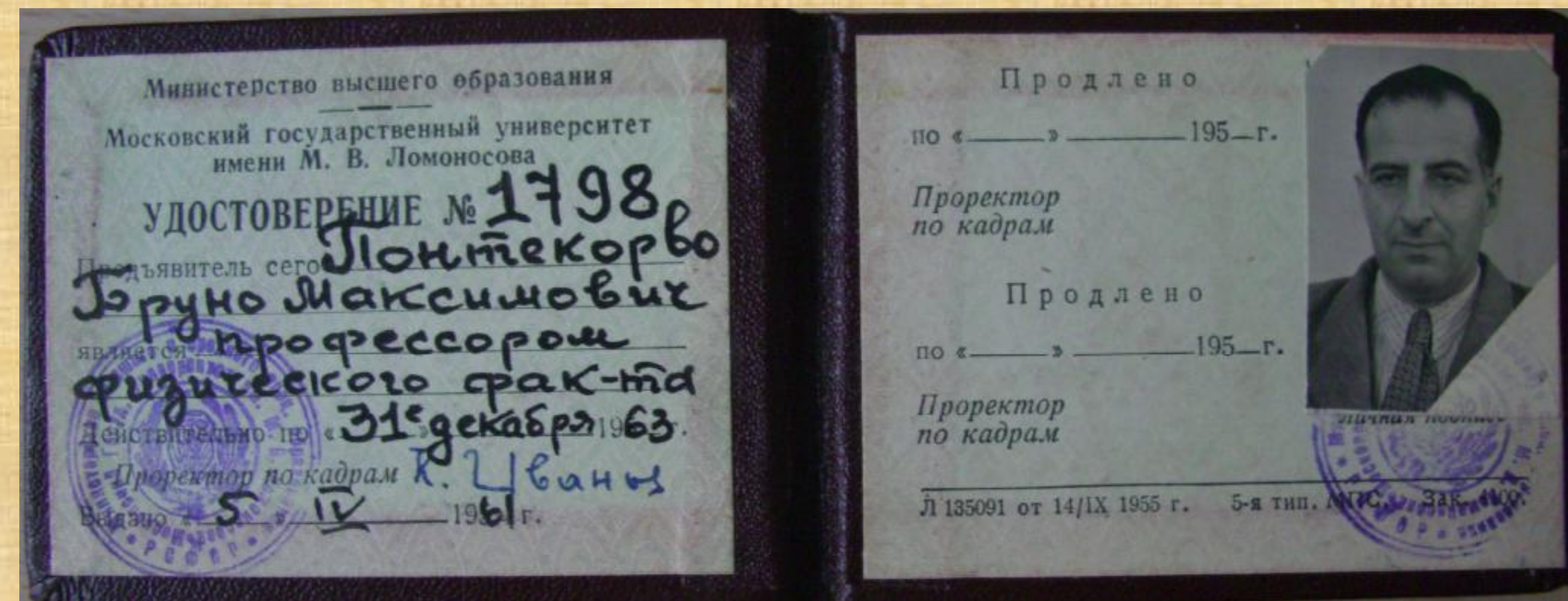
and, if not delayed, for π^0. (In this respect one should remember that the weighing of electrons versus star particles may be ≈ 10 in energy, for same energy loss.

b) Cherenkov detector.

Star detector

~~The st~~ An electronic star detector can be made on the basis of neutron production. It is true that neutrons are detected inefficiently, but, on the other hand, large masses can be used.

First Tennis Champion at Chalk River – 1948
Bruno Pontecorvo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