The unpublished notebooks of Bruno Pontecorvo in Russia

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Abstract

At the end of August 1950, while in a short vacation in Italy, Bruno Pontecorvo suddenly disappeared, along with his wife and three sons. Having choosen to work in Soviet Union, he has been often vilified for treachery, as the Italian scientist who passed the secrets of the atomic bomb to the Soviets and collaborated to the construction of the Russian hydrogen bomb. By studying the two Bruno's notebooks that his oldest son, Gil, gave us, we have been able to reconstruct, in detail, the research activity Pontecorvo performed at the Institute of Nuclear Problems in Dubna, from November 1, 1950 up to end of March 1952. The two notebooks contain unpublished notes, ideas and considerations he wrote by hand, mostly in English, during his early years of work in Russia. In both notebooks we have not find any reference to possible involvement in the atomic program of the Soviet Union while it emerges the figure of a brilliant physicist whose work strictly concerns basic researches in elementary particle physics.

The two secret notebooks

About three years ago, during a visit to the Joint Institute for Nuclear Research (JINR) in Dubna, one of us (G. S.) had the great privilege to receive, directly from the hands of Gil Pontecorvo, a notebook that belonged to his father Bruno [Fig.1, left]. The surprise was even greater reading the year printed on the cover, and the date, in Russian, on top of the first page: November 1st, 1950.

It was the notebook where the famous scientist, just arrived in the small village on the Volga river, had started to annotate his ideas on the research program he intended to develop at the Institute for Nuclear Problems of the USSR Academy of Sciences.

Bruno Pontecorvo had suddenly vanished, along with his wife and three sons, during a vacation in Italy at the end of August 1950. Only a few weeks earlier he had accepted appointment to a professorship at Liverpool University after having worked for two years at the British atomic research plant at Harwell. Nobody knew of him until March 4th, 1955 when, at the Academy of Sciences in Moscow, he held a press conference to explain the motivations that had led him to leave the West for the Soviet Union. In those days the international press gave great prominence to the news and in many newspapers Pontecorvo was vilified for treachery: the Italian scientist who had passed the secrets of the atomic bomb to the Soviets and collaborated to the construction of the Russian hydrogen bomb. Nothing could be further from the truth, as Bruno himself repeated in many occasions.

By studying his notebook we convinced ourselves of his absolute interest in pure scientific research and we did not find any reference to possible involvement in the atomic program of the Soviet Union.

Nevertheless we remarked something odd in the flow of notes that Bruno had reported in his first notebook: after few pages, in fact, where he started to annotate ideas about the experiments to be performed at Dubna synchrocyclotron and the particle detectors to be used, he suddenly stopped writing and some months after, on September 14th 1951, he resumed writing by turning upside down the notebook and beginning from the last page: the page number 100.

The lack of information about his activity research, for roughly one year, has originated speculations by the particle physicist Frank Close who thought of a possible involvement of the scientist on issues "*other than the initial inquiries*", as he writes in his book dedicated to Pontecorvo [1].

Close knew the content of the Bruno's logbook with roughly ten months of not reported activity, from a presentation done by one of us (R.C.) [2] at the Conference entitled "The Legacy of Bruno Pontecorvo: the Man and the Scientist" (Roma, 11-12 September 2013).

In his book Close writes that after an *"initial period of brainstorming",* Pontecorvo *"was apparently assigned another task until September 1951"* and that *"whatever he did in the intervening ten months was not part of that original program, and was thus not recorded in the logbook".*

Nevertheless, well before the publication of Close's book, we had already presented [3] to the 100th Congress of the Italian Physics Society (Pisa, 22-26 September 2014) a second notebook of Pontecorvo that Gil had given us a few months before. This notebook luckily covers exactly this time gap [Fig.1, right]!

Both notebooks consist of hundred numbered double pages where Pontecorvo records day after day his work at the Institute of Nuclear Problem. From the pages of these notebooks it emerges clearly the figure of a brilliant experimental physicist with extensive experience of the most advanced particle detectors and, at the same time, of a distinguished theoretical physicist whose work strictly concerns basic researches in elementary particle physics only.

The first notebook

On the 14th of December 1949 the five-meter Dubna synchrocyclotron was put into operation and 280 MeV deuterons and 560 MeV alpha particles beams were obtained. Only toward the end of 1950 the synchrocyclotron started to accelerate protons up to an energy of 480 MeV so a considerable part of the first investigations was devoted to the determination of important parameters of the produced particle beams, such as intensity, energy, angular distribution.

It is November 1st, 1950 when Bruno Pontecorvo starts recording in this secret notebook the work that he is doing with the Dubna synchrocyclotron.

The first considerations he writes down in this notebook concern the measurement of the energy of the neutron beams produced at the accelerator (*"Neutron production by cyclotron particles"*). He is attracted by the possibility to extract neutrons from the cyclotron and here suggests a method *"to get an idea of the neutron energy by measuring the space distribution of neutrons (for example measure* $|r^2|_{av.}$*)"* [Fig.2]. Intense neutron beams are in fact produced when exposing internal targets of different materials to the 560 MeV α-particles, but their energy distribution is unknown.

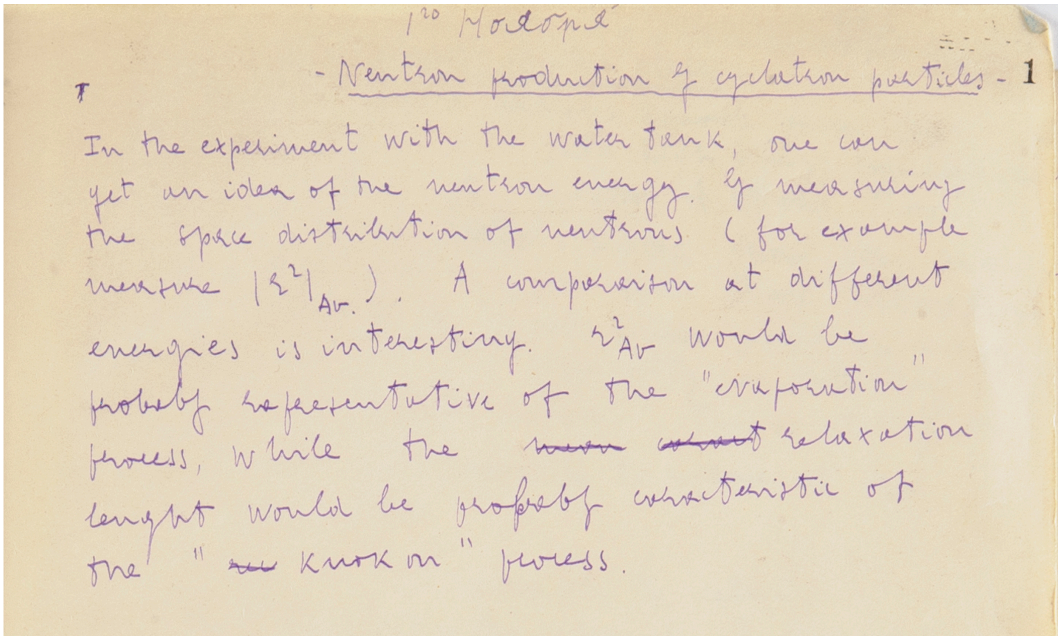
Fig.1 - The Pontecorvo's notebooks. Note the starting date written on the bottom left of the covers. First notebook (left): I/XI 1950. Second notebook (right): 30/XI 1950. The first notebook covers the periods 1 – 30 Nov. 1950 and 14 Sept. 1951 — 24 Mar. 1952, while the second notebook fills the time lag 30 Nov. 1950 — 18 Jul. 1951.

He knows that with such beams it is possible to study the properties of pion-nucleon interaction when neutral and charged pions are produced in nucleon-nucleon collisions on targets of hydrogen or complex nuclei. The interest in the production of pions with neutron beams is due to the fact that many experiments at that time have been conducted with proton beams but little or nothing with neutrons.

In the first eight pages of the notebook, Bruno annotates all his ideas in a long list of possible experiments to perform at the Dubna cyclotron:

- *excitation function of fission + neutron production in the π^- region;*
- *fission from highly excited states;*
- *multiple meson production;*
- *experiments on μ mesons;*
- *H^4 experiment;*
- *double meson production;*
- *experiment on radioactive indicator for mesons;*

- *experiment on how π^- capture (mass of π^0);*
- *production of π^- or π^+ in nucleon nucleon collisions n-p;*
- *production of electrons in nuclear interaction;*
- *detection of τ meson;*
- *on the transformation of mesons.*


1го ноября

- Neutron production by cyclotron particles - 1

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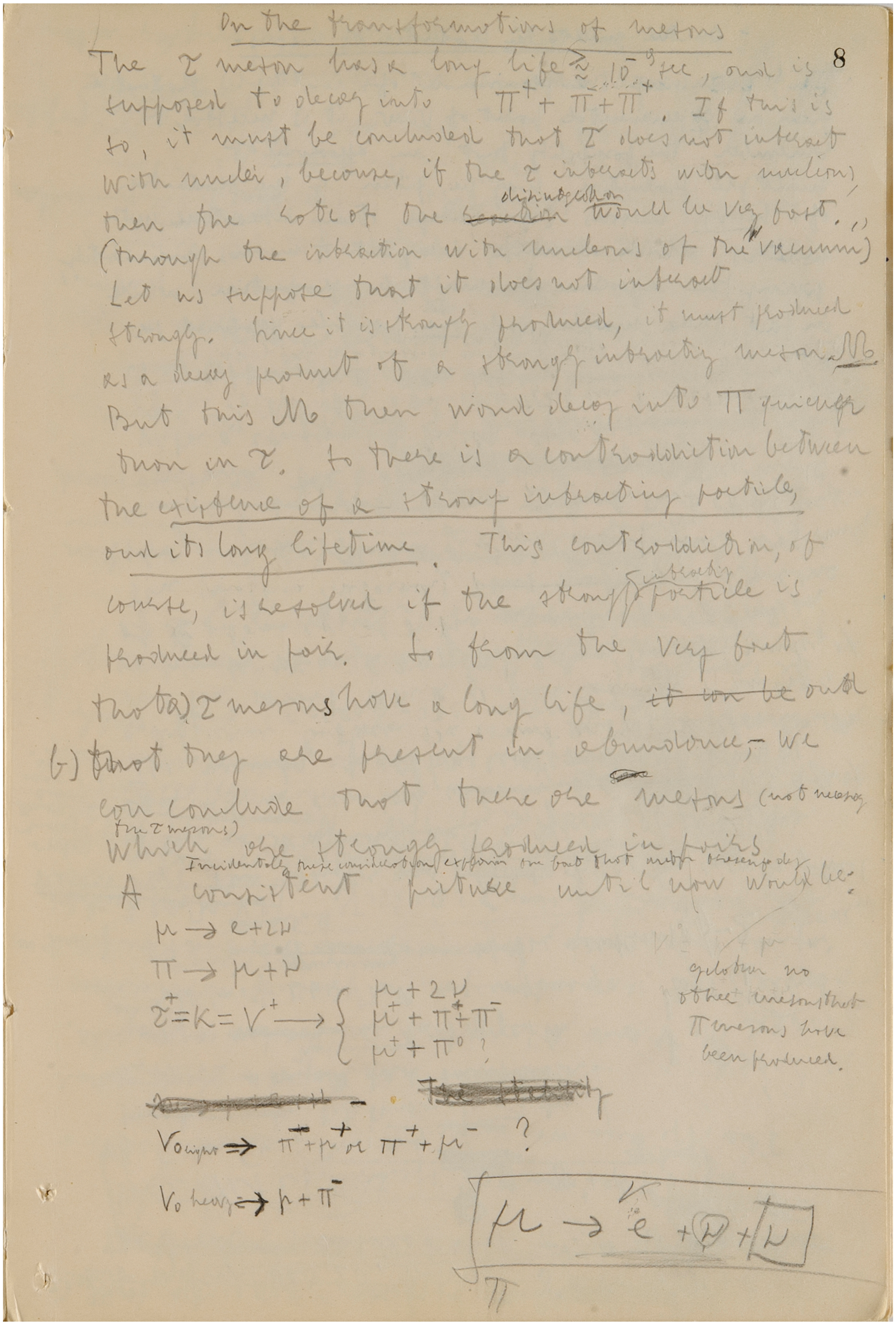
In the experiment with the water tank, one can get an idea of the neutron energy by measuring the space distribution of neutrons (for example measure $(r^2)_{Av.}$). A comparison at different energies is interesting. r^2_{Av} would be probably representative of the "evaporation" process, while the relaxation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

Fig.2 – The starting page of Bruno's first notebook, dated November the 1st (1го ноябрь).

On page 8, the last one before stopping to write on this notebook, Pontecorvo has a great intuition. He speaks about mesons decay, in particular about the long lifetime ($>10^{-9}$sec) of the τ meson (the former name of the K meson) which is supposed to decay in $\pi^+ + \pi^- + \pi^+$. *"If this is so"* - he writes - *"it must be concluded that τ does not interact with nuclei, because, if the τ interacts with nucleus, than the rate of the disintegration would be very fast (through the interaction with nucleons of the vacuum). Let us suppose that it does not interact strongly. Since it is strongly produced, it must (be) produced as a decay product of a strongly interaction meson* **M**. *But this* **M** *then would decay into* π *quicker than in τ. So <u>there is a contradiction between the existence of a strong interacting particle, and its long lifetime</u>. <u>This contradiction of course, is resolved if the strong interacting particle is produced in pair</u>"* [Fig.3].

These "strange" particles, recently discovered, decay with long lifetime via weak interaction while are produced in certain paired combinations through the strong interactions in high energy collisions of cosmic rays with nuclei of the atmosphere.


On the transformations of mesons

8

The τ meson has a long life $\gtrsim 10^{-9}$ 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. (through the interaction with nucleons of the vacuum) Let us suppose that it does not interact strongly. Since it is strongly produced, it must produced as a decay product of a strongly interacting meson M. But this M then would decay into π quicker than in τ. So there is a contradiction between the existence of a strong interacting particle, and its long lifetime. This contradiction, of course, is resolved if the strongly interacting particle is produced in pairs. So from the very fact that a) τ mesons have a long life, and b) 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 [illegible]

A consistent picture until now would be:

$\mu \to e + 2\nu$

$\pi \to \mu + \nu$

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

cyclotron no other mesons that π mesons have been produced.

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

$V_0 \text{ heavy} \Rightarrow p + \pi^-$

$\mu \to e + \nu + \nu$

Fig.3 - A very interesting page of the first notebook, the page n. 8. Pontecorvo writes these annotations on November 1950.

It must be noted that Pontecorvo postulates the hypothesis of associated production in November 1950 [4], two years before the famous article by Abraham Pais [5] where the author devises a scheme of interaction using the conventional field theory.

In 1953 Bruno performs an experiment at the Dubna accelerator to check if the hypothesis is true; namely, he wants to check that it is not possible to produce single Λ^0 hyperons in strong interactions between protons and nucleons, being the energy of the accelerator not enough to produce them in pair with the K mesons. The results of the experiment, "On t*he possibility of the formation of* Λ^0*-particles in collisions of 680 MeV protons with carbon nuclei*" [6], confirms his hypothesis.

The experimental evidence of the theory of associated production of strange particles arrives shortly later in 1953 with the experiments at the Cosmotron of Brookhaven [7] and subsequently at the Bevatron of Berkeley, thanks to the sufficiently high energy of both accelerators. Those results demonstrate that in the strong interaction the strangeness is conserved while this quantum number can be violated by weak interaction in decays that are therefore with long lifetime.

The researches of Pontecorvo on the strange particles are never, or almost never, cited as one of the main contribution to the ideas that have led to the quark model and then to the Standard Model of Particle Physics; but the demonstration that already in 1950 he had the intuition of the solution of the contradictory behavior of these strange particles is written on the page 8. Unfortunately, this idea has remained hidden in his notebook and in some internal reports written in Russian, not accessible to the physics community outside the Soviet Union, for a long time.

There is another very interesting annotation on page 8. Just under the text *"a consistent picture until now would be:"* he writes the muon decay as $\mu \rightarrow e + 2\ \nu$, but a few lines below, towards the end of the page, he rewrites the decay as $\mu \rightarrow e + \nu + \nu$, highlighting the two neutrinos with different signs.

Does Pontecorvo already suspect the different nature of the two neutrinos from the muon decay process? The note comes twelve years before this hypothesis is experimentally validated.

Eight years later, in 1958, at the Laboratory of Nuclear Problems in Dubna a high intensity 800 MeV proton cyclotron is planned to be built. It is a good opportunity for Pontecorvo to demonstrate that the two neutrinos from the muon decay are not the same particle. In the same way the antineutrino of the pion decay ($\pi^- \rightarrow \mu^- +$ anti-ν_μ) differs in nature from the antineutrino of the β decay. In the paper "*Electron Muon and Neutrino*" [8] he suggests a long list of reactions induced by neutrinos (or antineutrinos) that cannot occur if the two neutrinos (or antineutrinos) are of different types, i.e. one associated to the electron (ν_e) and the other to the muon (ν_μ). With simple arguments of symmetry between charged leptons (electron and muon) and corresponding neutral leptons (neutrinos), Pontecorvo realizes that there must be two different types of the neutrinos: electron and muon neutrinos. "*There are no reasons for asserting that ν_e and ν_μ are identical particles*", he writes in the article and then he continues with a series of considerations that favor the hypothesis of different types of neutrinos. In particular Pontecorvo suggests to use the new powerful accelerator, under design, to produce an anti-ν_μ beam from pion decays. He wants to prove that the reaction anti-$\nu_\mu + p \rightarrow e^+ + p$ is forbidden while the reaction anti-$\nu_\mu + p \rightarrow \mu^+ + n$ is possible. Unfortunately the 800

MeV cyclotron was never built in Dubna so Pontecorvo could never perform the experiment!

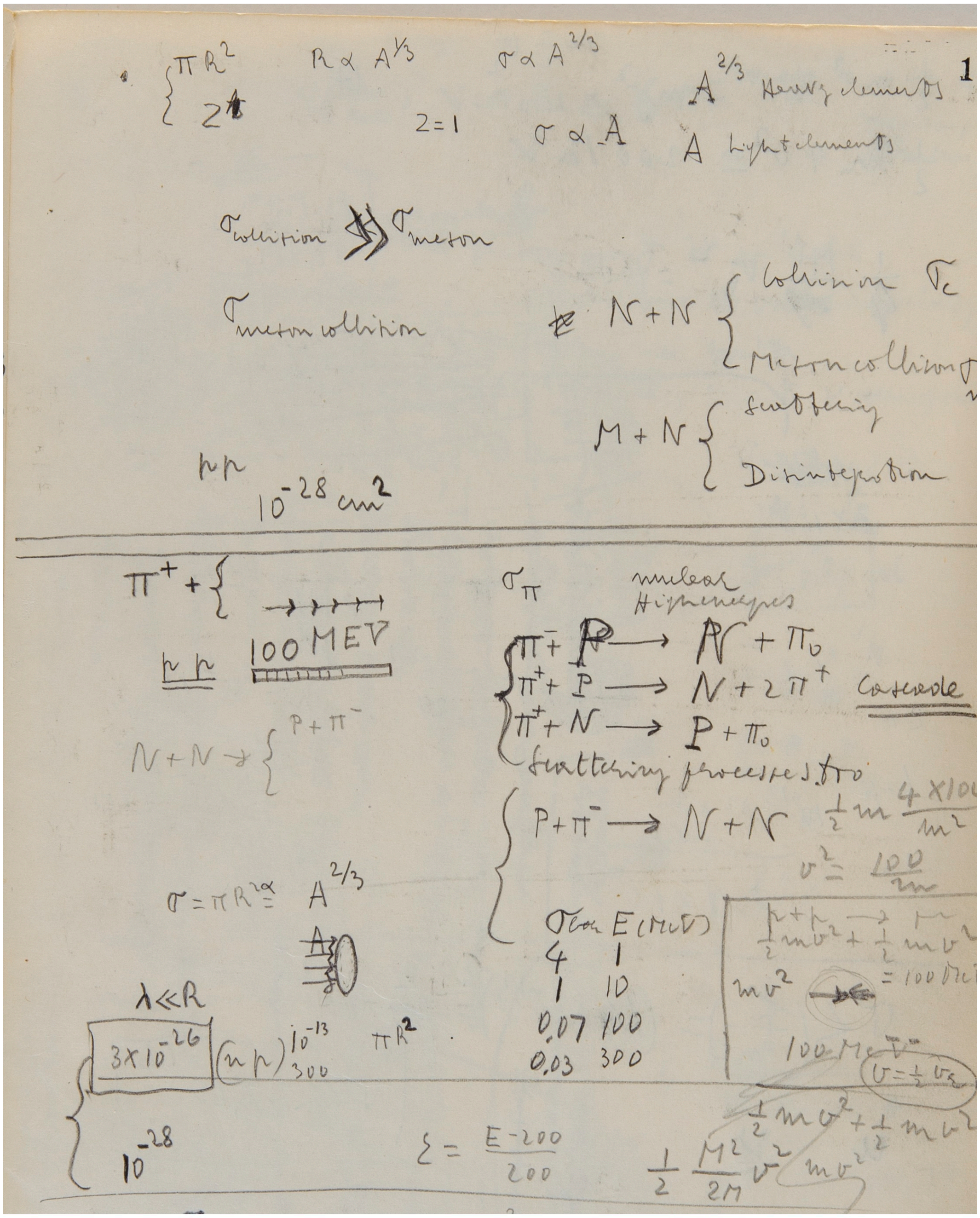


Fig.4 – The first page of the second notebook.

Three years later, at the Brookhaven AGS, L.M. Lederman, M. Schwartz and J. Steinberger observed the existence of two kinds of neutrinos, i.e. they proved that $\nu_\mu \neq \nu_e$ [9]. For this discovery they were awarded the Nobel Prize in 1988.
But let's go back to the notebook.

On page 9, Pontecorvo starts to write a draft entitled *"On the multiple production of mesons"*. He continues for few lines then, abruptly, stops writing and, as we know now, he begins to use another, new, notebook. On its cover it is written the starting date: November 30, 1950.

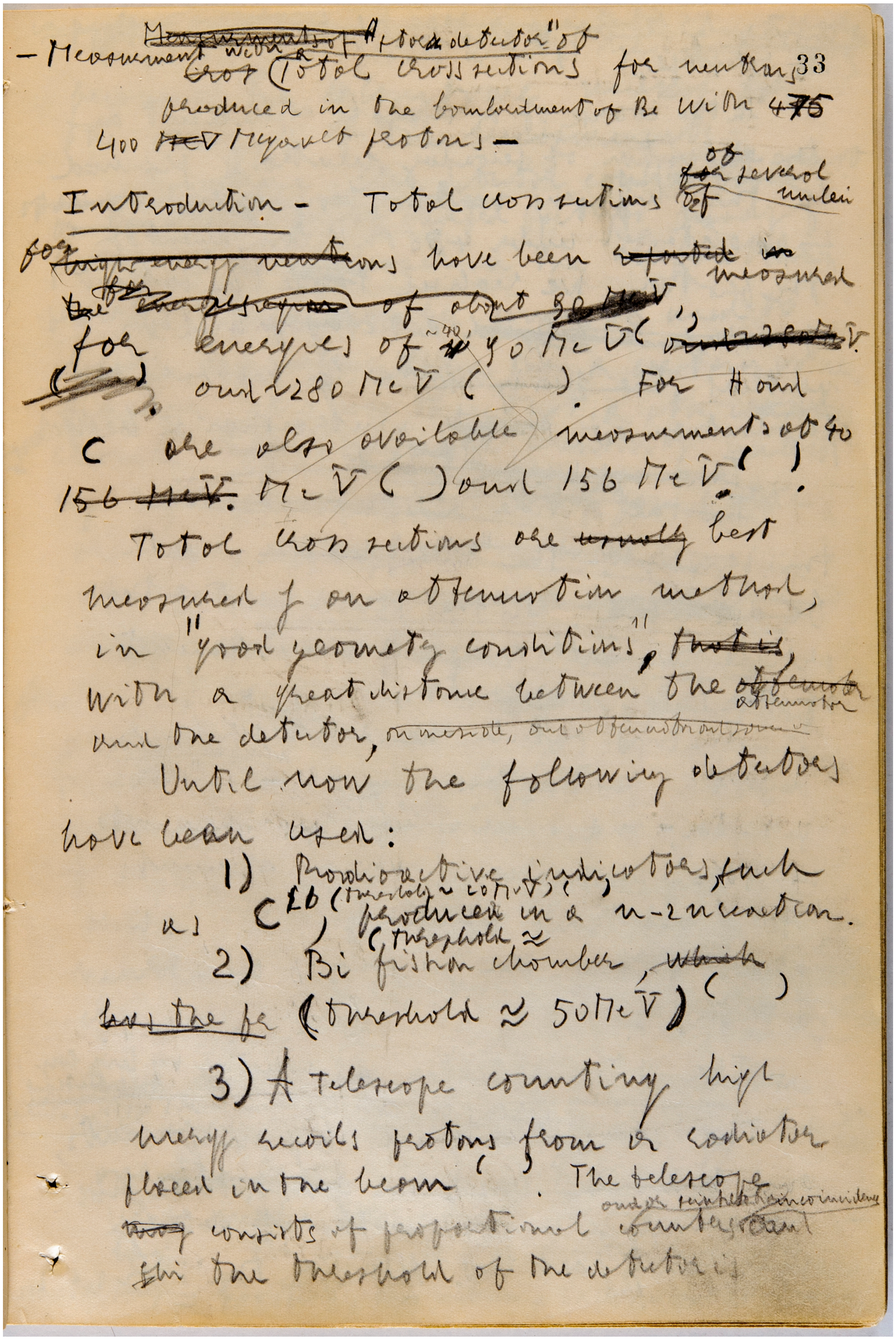
The second notebook

He starts the new notebook with geometric considerations on the order of magnitude of the total cross section for mesons production in nucleon-nucleon and nucleon-nuclei collisions and goes on for a few pages with these calculations, often scribbling numbers, formulas and graphics in a disorderly manner maybe just to fix thoughts and ideas that swirl in his mind.

Fig.4 shows the first page of this second notebook. Pontecorvo is very interested to study the total cross sections of various nuclei with the neutrons produced in the bombardment of Berillium by 400 MeV protons. Many pages of the second notebook are dedicated to the description of this measurement. In a draft of an article, Pontecorvo describes the detector used, that he calls "star detector", and the measurements of total cross section of various elements obtained by using the "attenuation method" which, as he says, is *"the best in the case of good geometry conditions, with a great distance between the attenuator and the detector "* [Fig.5].

Pontecorvo has already observed the production of secondary neutrons by high energy neutron beams in light elements and he is now interested to detect these high energy neutrons by measuring the secondary production in heavy elements.
He asserts that "the Stars", typical big energy events observed in photographic emulsions, *"are in principle a good method of detecting high energy particles"*, and suggests other two ways of detection: a *"ionizing chamber, as alternative star detector to emulsions"* to reveal the ionizing charged particles, mainly protons and α's, released in the evaporation process, or, even better, the use of a neutron counter. "*However "* - he writes - "*it is easy to see that a star ionization chamber in practice has a very small sensitivity, unless very high pressures of a heavy gas like Xe are used. A different solution of the process is to detect neutrons (..) emitted in the evaporation process. This method has the advantage that a very high thickness of star producing material (order of a mean free path of the high energy neutrons) can be used. It is true that the secondary neutrons will be detected with a small efficiency (≈ 10^{-4}); however the high multiplicity of neutron production per inelastic collision (≈ 10 in a heavy element) and the very large thickness which can be used make the overall sensitivity high (pag. 34)"*.

Pontecorvo is an expert of both techniques since the times of "Via Panisperna". For the experiment he decides to adopt the arrangement he calls "long counter arrangement", consisting of a Boron Trifluoride (BF_3) neutron counter imbedded in a paraffin block. This kind of proportional counter employs the $B^{10}(n,\alpha)Li^7$ reaction to detect thermal neutrons.



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– Measurement with a "star detector" of total cross sections for neutrons produced in the bombardment of Be with 400 Megavolt protons –

Introduction – Total cross sections of several nuclei for high energy neutrons have been measured for energies of ~40 MeV ( ) and 280 MeV ( ). For H and C are also available measurements at 40 MeV ( ) and 156 MeV ( ).

Total cross sections are best measured by an attenuation method, in "good geometry conditions", with a great distance between the attenuator and the detector.

Until now the following detectors have been used:

1) Radioactive indicators, such as C^{11} (threshold ~ 20 MeV) ( ) produced in a n-2n reaction.

2) Bi fission chamber (threshold ≈ 50 MeV) ( )

3) A telescope counting high energy recoils protons from a radiator placed in the beam ( ). The telescope consists of proportional counters and/or scintillation coincidence the threshold of the detector is

Fig5. - Draft of "*Measurement with a "star detector" of total cross sections for neutrons produced in the bombardment of Be with 400 Megavolt protons"* (pag. 33).

A few pages of the notebook are dedicated to the description of the whole detector system, i.e. a Pb absorber cube in the neutron beam + the "long counter" outside the beam.

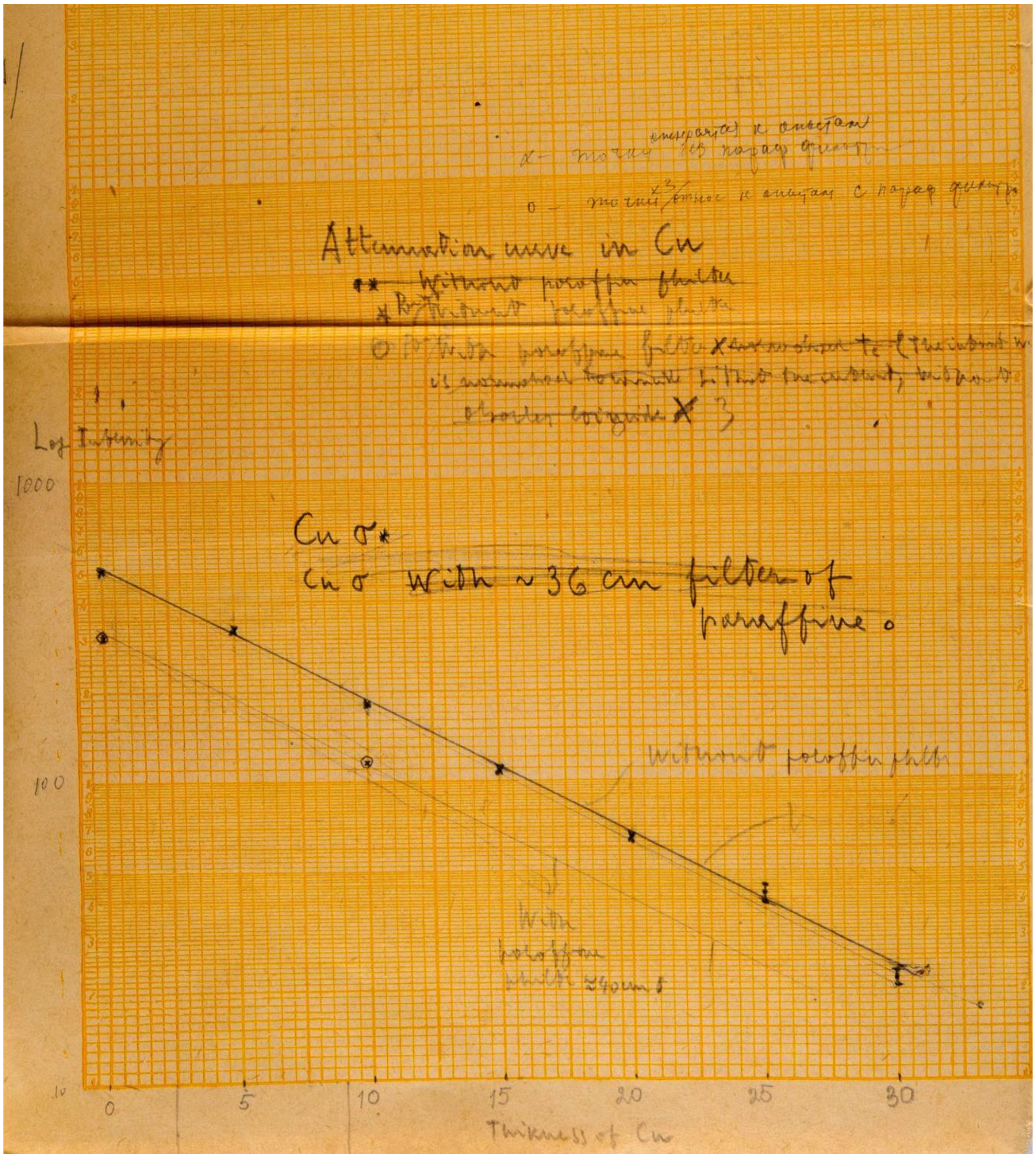


Fig.6 - The plot of the attenuation curve in Cu.

These pages, as many others of the manuscript, are difficult to read because of the innumerable erasures, corrections, and marginal insertions. Despite this, one can follow the rather detailed discussion on the advantages and disadvantages of such a detector and its energy response.

To evaluate the total cross section Pontecorvo uses the "absorption method". He plots the logarithmic neutron intensity, background subtracted, as a function of the absorber thickness [see Fig. 6]. From the exponential shape of the absorption curve, Pontecorvo infers that *"the primary neutron spectrum N(E) is not rich in low energy* *neutrons and that the absence of a real threshold in the detector did not affect considerably the result (in pag. 50)".*

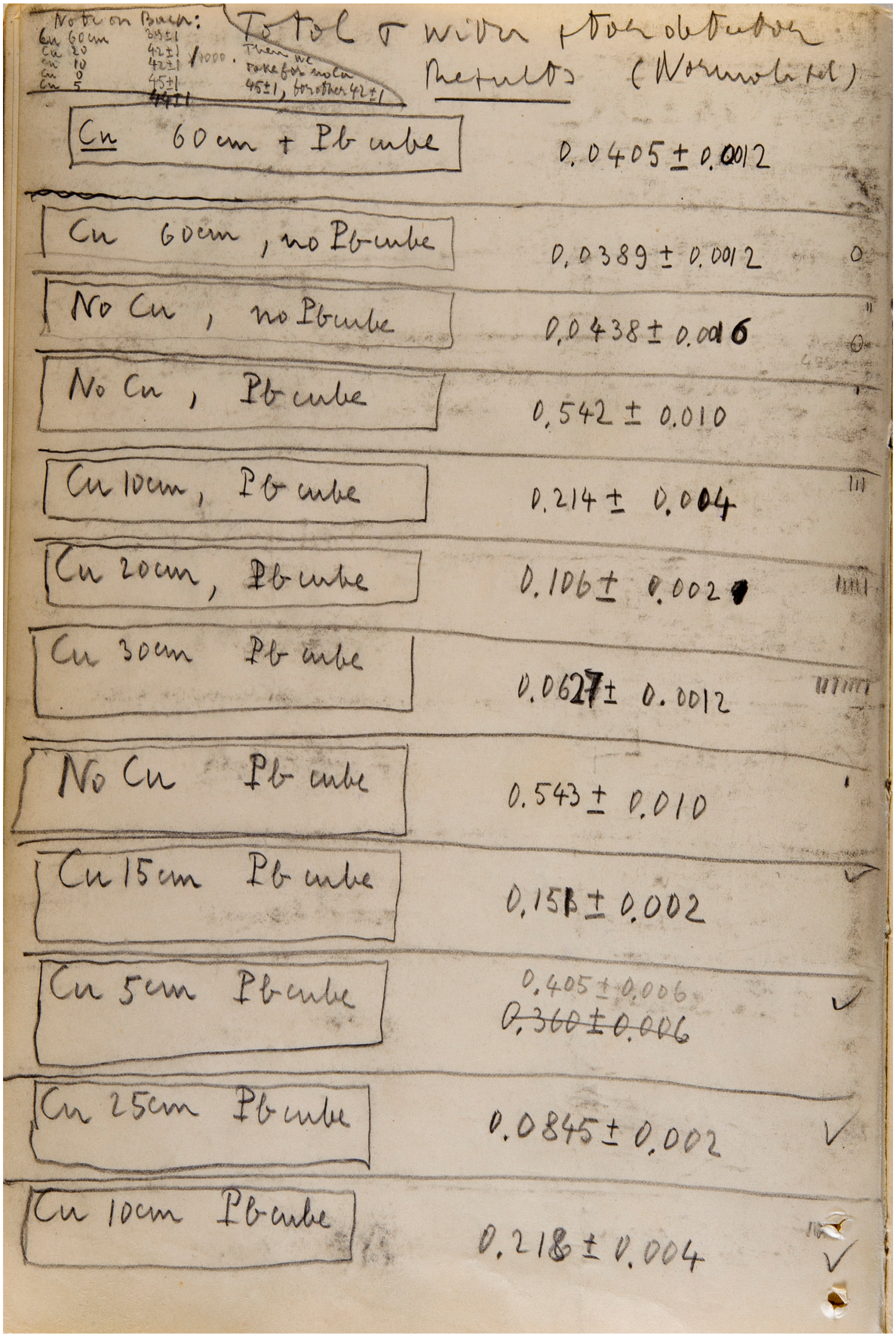
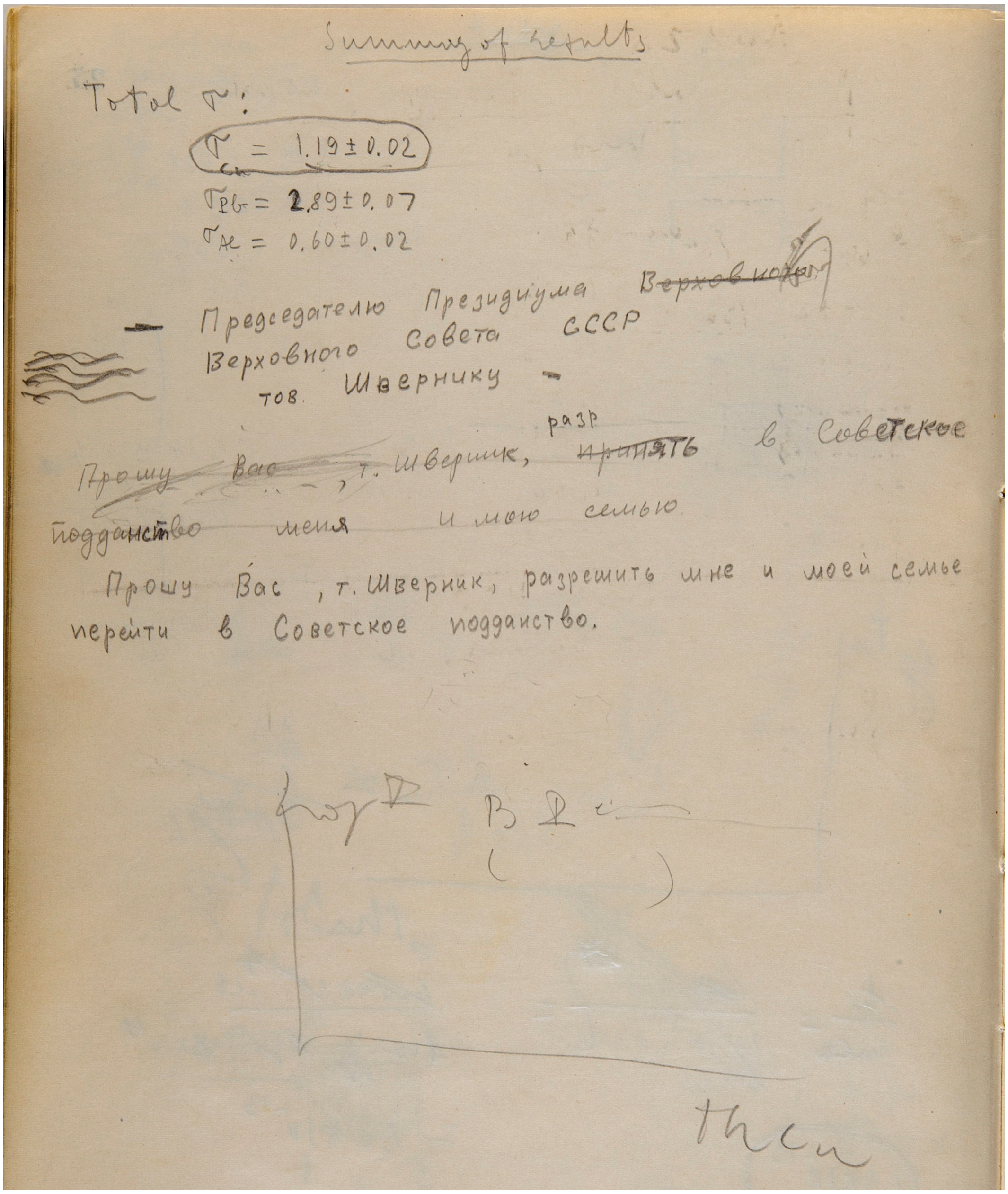


Fig.7 - Measurements in Cu of total cross section with the "Star detector".



Summary of results

Total σ:

$\sigma_{Cu} = 1.19 \pm 0.02$

$\sigma_{Pb} = 2.89 \pm 0.07$

$\sigma_{Al} = 0.60 \pm 0.02$

Председателю Президиума ~~Верховного~~
Верховного Совета СССР
тов. Швернику

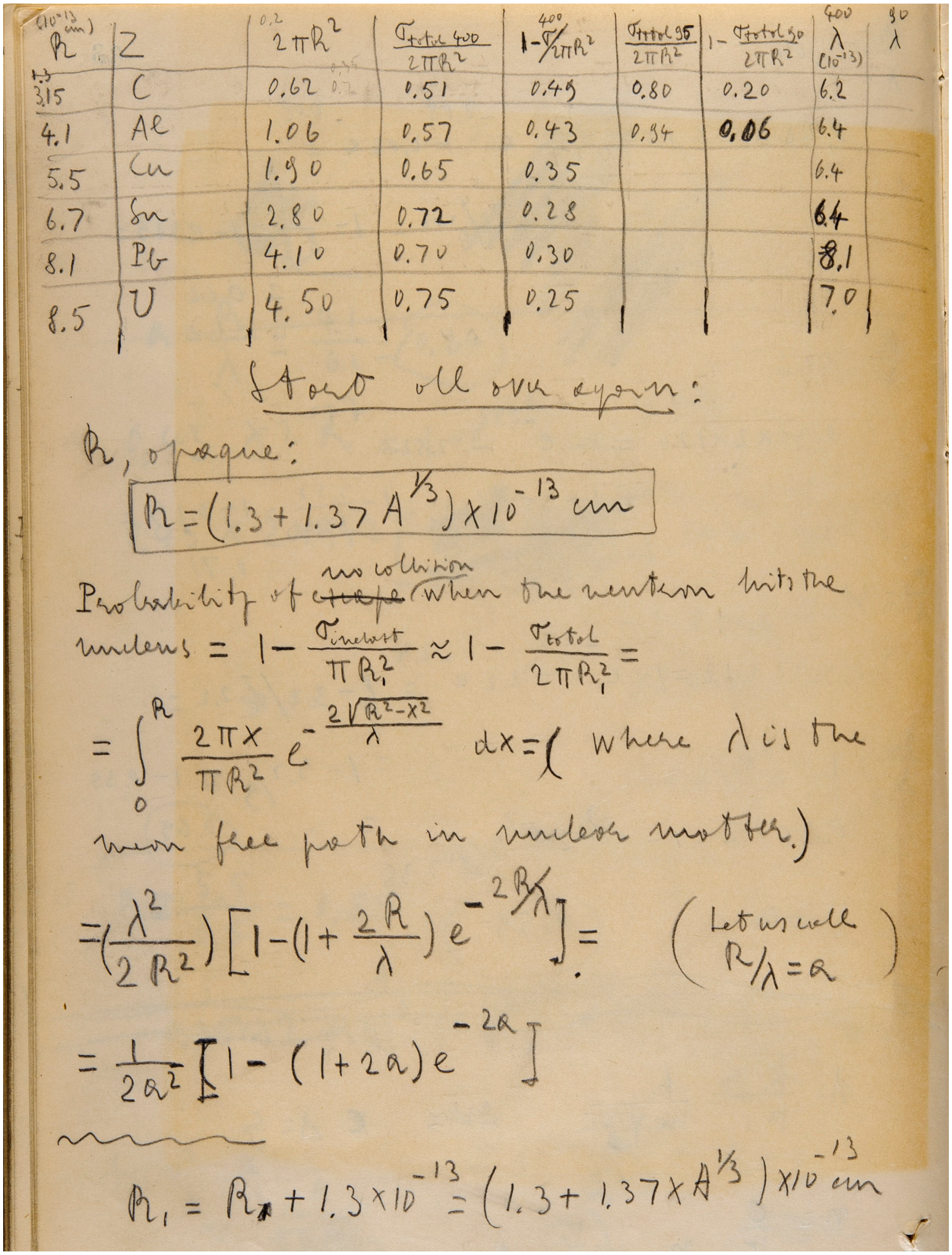
~~Прошу Вас~~, т. Шверник, разр ~~принять~~ в Советское подданство меня и мою семью.

Прошу Вас, т. Шверник, разрешить мне и моей семье перейти в Советское подданство.

Fig.8 – Results of the measurements of total cross section for different elements. Below the draft of application for soviet citizenship that Pontecorvo asks for the whole family.

Fig.7 shows the page of the notebook in which Pontecorvo lists the normalized values of the beam intensity he has measured with the star detector, for different thickness of the copper absorber.

The results for Cu, Pb and Al are summarized on page 25 [Fig. 8]. The measurements of total cross section are extended to other complex nuclei as Carbon, Tin, Lead, Uranium and the results are reported in neighboring pages of the notebook.



R (10^{-13} cm)	Z	$2\pi R^2$	$\frac{\sigma_{total\,400}}{2\pi R^2}$	$1-\sigma/2\pi R^2$ (400)	$\frac{\sigma_{total\,95}}{2\pi R^2}$	$1-\frac{\sigma_{total\,90}}{2\pi R^2}$	λ (10^{-13}) 400	λ 90
3.15	C	0.62	0.51	0.49	0.80	0.20	6.2	
4.1	Al	1.06	0.57	0.43	0.94	0.06	6.4	
5.5	Cu	1.90	0.65	0.35			6.4	
6.7	Sn	2.80	0.72	0.28			6.4	
8.1	Pb	4.10	0.70	0.30			8.1	
8.5	U	4.50	0.75	0.25			7.0	

Start all over again:

R, opaque:

$$R=(1.3+1.37A^{1/3})\times 10^{-13}\ \text{cm}$$

Probability of ~~escape~~ no collision when the neutron hits the nucleus $= 1-\frac{\sigma_{inelast}}{\pi R_1^2} \approx 1-\frac{\sigma_{total}}{2\pi R_1^2} =$

$$= \int_0^R \frac{2\pi x}{\pi R^2} e^{-\frac{2\sqrt{R^2-x^2}}{\lambda}}\,dx =$$ (where λ is the mean free path in nuclear matter.)

$$= \left(\frac{\lambda^2}{2R^2}\right)\left[1-\left(1+\frac{2R}{\lambda}\right)e^{-2R/\lambda}\right] =$$ (Let us call $R/\lambda = a$)

$$= \frac{1}{2a^2}\left[1-(1+2a)e^{-2a}\right]$$

$$R_1 = R + 1.3\times 10^{-13} = (1.3+1.37\times A^{1/3})\times 10^{-13}\ \text{cm}$$

Fig.9 - The opaque nucleus model interpretation of the total cross section.

In the central part of the page 25 there is the draft of a letter for the request of soviet citizenship for the whole family. The letter is addressed to the Chairmen of the Presidium of the Supreme Soviet of the USSR, Nikolay M. Shvernik, President of USSR from 1946 to 1953. Pontecorvo forgets for a while physics problems and practices writing in Russian:

"*President of the Presidium of the Supreme Soviet of the USSR*
Comrade Shvernik

Tovarich Shvernik, I ask you to allow me and my family to become a Soviet citizen."

On top of next page (pag. 26) there is a date: April 26. The year is 1951. In 1952 Bruno Pontecorvo obtains the Soviet citizenship and three years later he joins the Communist Party.
In the following pages of the notebook Pontecorvo interprets the measurements of the total cross section in terms of the "opaque nucleus model" [Fig.9], a sort of optical model that take into account the reabsortion inside the nucleus. He writes: *"The nuclear radius R is defined conventionally by the empirical relation* $R=(1.3+1.37A^{1/3})10^{-13}$*, which is the best fit to data of total cross section for neutrons of ~ 15 MeV (opaque nucleus model)"* (pag. 74).

Nowadays a good description of the neutron-nucleus experimental total cross sections is given by the phenomenological Ramsauer model, a modified version of the optical model [10] not too much different from the model used in this notebook.

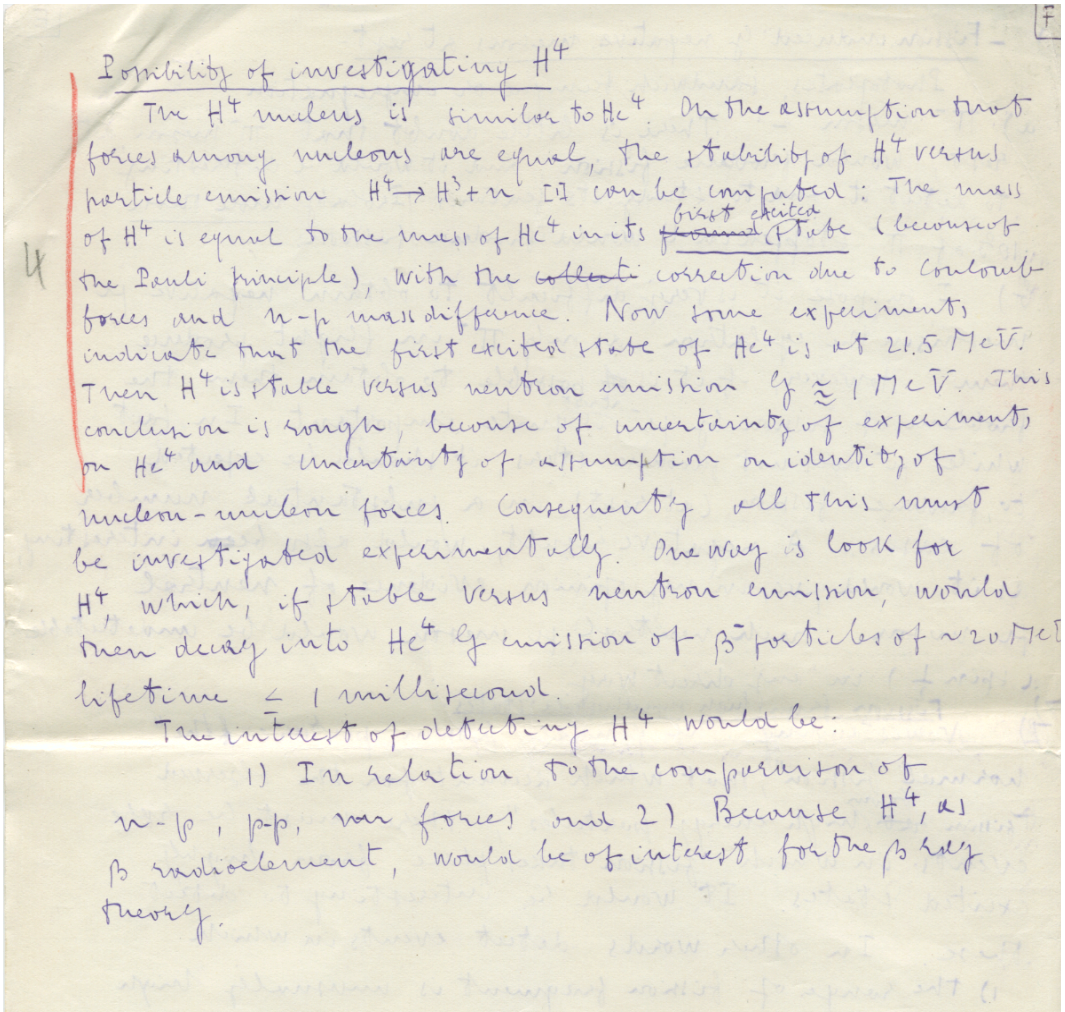
Pontecorvo is very interested to mesons production in collision of nucleons with complex nuclei. He follows the results on the measurement of the π^+/π^- ratio obtained in experiments done in the meantime in the West. In the notebook there is a list of references to articles on this subject published in the Physical Review journal [11,12,13] and some notes about a seminar he is going to held on it (pages 61-62).

He is also interested to the possibility of investigating H^4, a heavy hydrogen state (one proton and three neutrons) and in both his notebooks he returns many times on this subject. He explains that *"the interest of detecting* H^4 *would be: 1) In relation to the comparison of n-p, p-p, n-n forces and 2) Because* H^4*, as β radioelement, would be of interest for the β ray theory"* [Fig.10]. Pontecorvo suggests one way to look for H^4, which *"if stable versus neutron emission, would then decay into* He^4 *by emission of* β^- *particles of ~ 20MeV and lifetime ≤ 1 millisecond"*, according the reaction: $H^4 \rightarrow He^4 + \beta + \nu$.

In the summer of 1951 Pontecorvo is defining the work program for the new year (few pages before the date of 11th of July is reported). Among the experiments to be done in the next few months, the investigation on H^4 is the first. He proposes to detect the *"hypothetical"* β^- particles by *"curving them in the cyclotron magnetic field and registering in 3 counters in coincidence, placed at a distance ≥ 10 cm from the cyclotron target. (....) The* H^4 *could be produced in the target by nuclear interactions: for example*

$$Li^8 \text{ excite} \rightarrow H4 + He^4 \text{ or } \pi^- + He^4 \rightarrow H^4 + He^4$$

If the first experiment is successful, it will take about a year to investigate the properties of H4 (spectrum, lifetime), and also to study in what condition it is produced. If the first experiment is not successful, other methods are considered" (pag. 85). Pontecorvo suggests to use a big liquid scintillation counter or a proportional counter in which the delayed ≈ 50 keV recoiling α can be detected. He concludes that a negative result on H^4 is not significant,*"however the techniques developed may be used in other problems"*.



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Possibility of investigating H^4

4 The H^4 nucleus is similar to He^4. On the assumption that forces among nucleons are equal, the stability of H^4 versus particle emission $H^4 \rightarrow H^3 + n$ [?] can be computed: The mass of H^4 is equal to the mass of He^4 in its ~~ground~~ first excited state (because of the Pauli principle), with the ~~collecti~~ correction due to Coulomb forces and n-p mass difference. Now some experiments indicate that the first excited state of He^4 is at 21.5 MeV. Then H^4 is stable versus neutron emission by $\gtrsim$ 1 MeV. This conclusion is rough, because of uncertainty of experiments on He^4 and uncertainty of assumption on identity of nucleon-nucleon forces. Consequently all this must be investigated experimentally. One way is look for H^4, which, if stable versus neutron emission, would then decay into He^4 by emission of β^- particles of ~20 MeV lifetime $\leq$ 1 millisecond.

The interest of detecting H^4 would be:

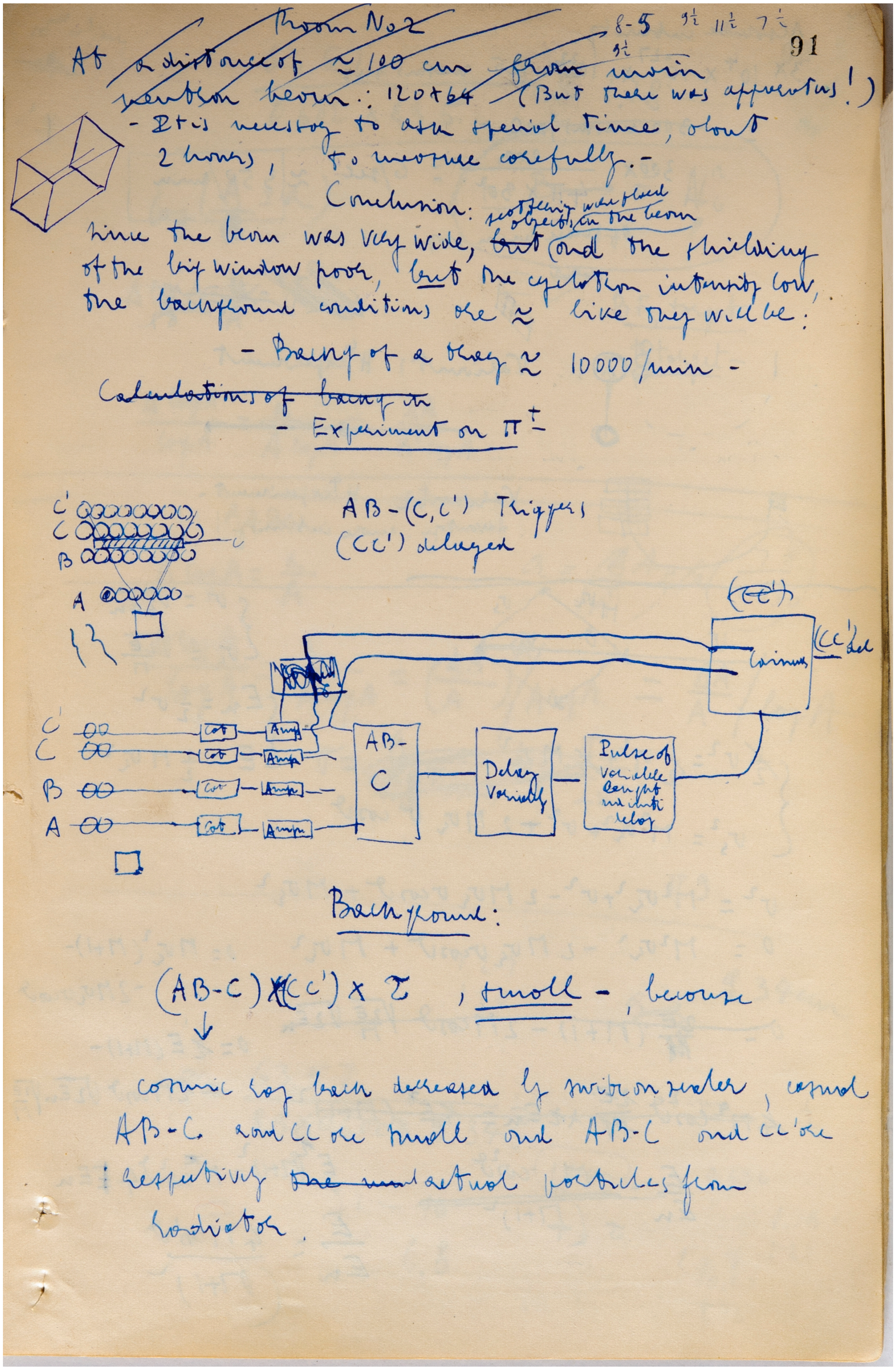
1) In relation to the comparison of n-p, p-p, nn forces and 2) Because H^4, as β radioelement, would be of interest for the β ray theory.

Fig.10 - On the possibility to investigate H^4.

The search of a bound state of the H^4 radioactive nuclei is still an open question but no evidence of his existence has been found yet [14,15,16].

In the last pages of the notebook, Pontecorvo continues to lists the future experiments:

- *Applications of the method of radioactive indicators to the investigation of properties of mesons;*
- *Development of techniques capable of detecting electronically mesons. Investigation of π^+ production in hydrogen and other elements by neutrons;*
- *Direct detection of meson beam (+and -) in the cyclotron with proportional counters. Application to the measure of π^+/π^- ratio;*
- *Development of Cherenkov detectors, for the study of relativistic particles.*



~~Room No 2~~ 8-5 9½ 11½ 7½

At ~~a distance of ≃ 100 cm from main neutron beam:~~ 120+64 (But there was apparatus!)

- It is necessary to ask special time, about 2 hours, to measure carefully.-

Conclusion: scattering was placed objects on the beam

Since the beam was very wide, ~~but~~ and the shielding of the big window poor, but the cyclotron intensity low, the background conditions are ≃ like they will be:

- Background of a day ≃ 10000/min -

~~Calculations of background~~

- Experiment on $\pi^{\pm}$ -

AB-(C,C') Triggers
(CC') delayed

Background:

(AB-C) × (CC') × τ, small -, because

cosmic ray back decreased by switch on scaler, cosmic AB-C and CC' are small and AB-C and CC' are respectively actual particles from radiator.

Fig.11 - Notes on the preparation of the experiment in Room 2.

The latest date on the notebook is July 18th (1951). Only 9 pages remain to the end. Pontecorvo describes the activities in preparation to the planned experiments with neutron beams that start simultaneously in the experimental halls (Room 2 and 3) of the cyclotron building [Fig. 11].

The operations of shielding and cabling of the counters are completed. The read-out electronics is assembled and the counters coincidence system checked. The beam characteristics and the background level are measured. He records all these steps in this notebook concluding:

"*since the beam was very wide, nothing absorbing was placed in the beam, and the shielding of the big window poor, but the cyclotron intensity low, the background conditions are ≈ like they will be"* (pag 91).

Back to the first notebook

It is September 14, 1951. Pontecorvo begins writing again in the first notebook from the last page, after having turned it upside down. He describes the "*Experiment on production of mesons by neutrons"* [Fig. 12]. The experiment is devoted to the problem of single production of charged and neutral π mesons in collisions between nucleons.

He starts from the π^0 meson production and detection and writes:

" 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 for γ radiation T ..."* (pag. 100).

The results of this experiment, in particular the study of the π^0 production, are reported in an internal report dated September 25, 1952 that Gil Pontecorvo found on the shelves of the JINR's library [17]. The paper was published again in 1955 [18].

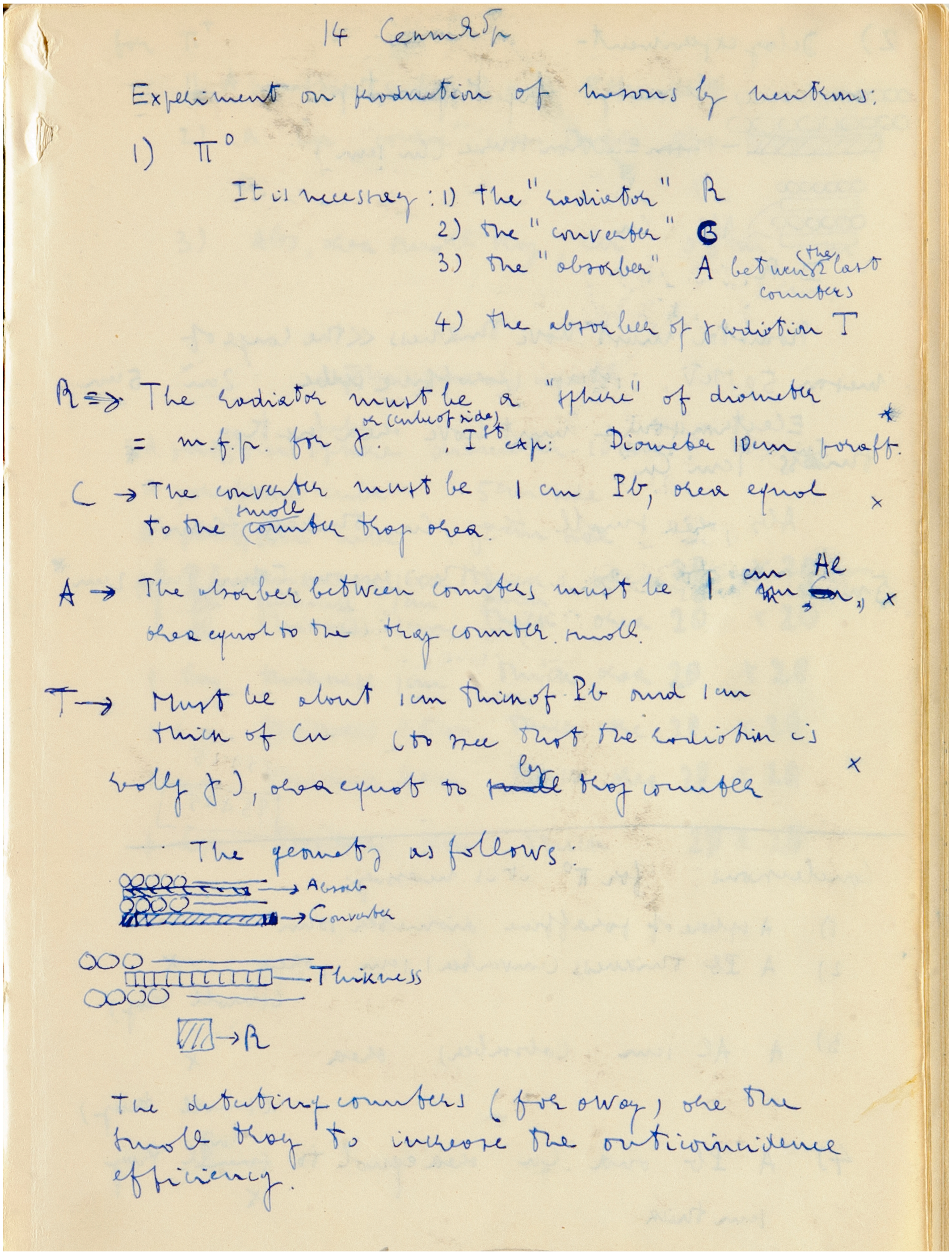
Between 1951 and 1955, according to the researches described in these notebooks, Bruno performs a series of experiment to confirm that proton and neutron, which are different particles for what concerns the electromagnetic interaction, are indistinguishable respect to the strong nuclear force. Proton and neutron are essentially the same particle in two different states of a new quantum number called isotopic spin.

From the pages of both notebooks it emerges the figure of a young scientist who coordinates the experiments and the activities of his group with expertise and scientific rigor. Pontecorvo considers the good collaboration among the team members a very important issue, and, in a gentle but peremptory way, he reproves his smart and ambitious colleagues who do not collaborate with each other: *"There were many examples where members of our group, for example, went for advice in electronics to other group, while there exists in our group a very well qualified man in electronics (...) the situation was not satisfactory and we must change it radically for the interest of the total scientific production of the group"* [Fig.13].

He suggests the creation of a team of specialists to develop electronic equipments for all the experimental groups of the laboratory, but he adds that this solution can work only if an *"absolute equality of status between the profession in electronics and the profession on nuclear physics"* is guaranteed.

The scientific interest of Pontecorvo goes far beyond the scattering experiments of nucleons and mesons on nuclei, although important. When he arrives in Dubna has already given fundamental contributions to the understanding of the weak interaction mechanism and therefore one should not wonder if, as we saw in page 8 of this notebook, many of his reflections concern the true nature of neutrinos and the study of the so-called strange particles. In 1947, after the famous experiment of Conversi, Pancini and Piccioni

[19] and its interpretation by Fermi, it was clear that the mesotron (now called muon), discovered by Anderson in 1937, was not the Yukawa particle (the π meson).


14 Сентябр

Experiment on production of mesons by neutrons:

1) π^0

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

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

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

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

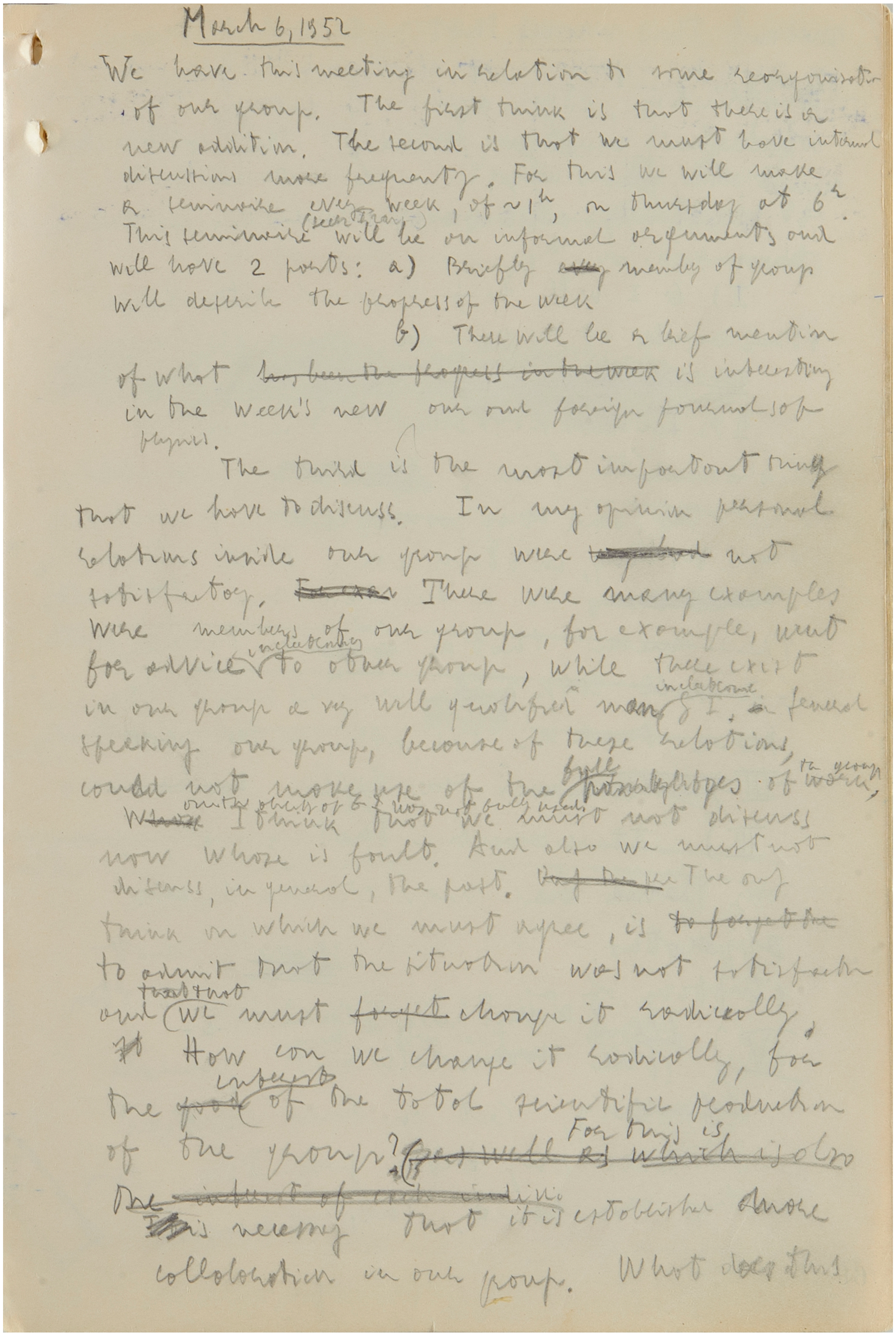
T → Must be about 1 cm thick of Pb and 1 cm thick of Cu (to see that the radiation is really γ), area equal to by tray counter ×

The geometry as follows:

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

Fig.12 – Pontecorvo turns upside down the notebook and starts to write this page. On top there is a date, written in Russian: September 14 (1951).

Indeed, unlike the π meson, which is a strongly interacting particle, the muon interacts much weaker with the nucleus.


March 6, 1952

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

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

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

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

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

Fig.13 - Minutes of the group meeting: March 6, 1952.

After reading the article by Fermi and collaborators on the decay of negative mesotrons in matter [20], Pontecorvo publishes in Physical Review, the paper entitled *"Nuclear capture of mesons and mesons decay"* [21]. In this article he observes that the nuclear capture probability of an electron and of a muon are practically identical (if account is taken of the large factor due to kinematic effects that depends from the mass difference of the two particles) and he concludes that: *"there exists fundamental analogy between β-processes and processes of emission and absorption of charged mesons"*.

Pontecorvo is the first scientist to conceive the idea of muon-electron universality which the basis of the whole theory of weak interactions.

Shortly after the Fermi's theory of the β-decay (1934), Bethe and Peierls [22] showed that the cross section of neutrino interaction with nuclei is extremely low, $< 10^{-44}$ cm^2 at MeV energies,*"corresponding to a penetrating power of 10^{16} km in solid matter"*, as the authors wrote in this paper. For this reason the neutrinos was considered an undetectable particle for many years. Pauli himself wrote to a friend that he had *"predicted something which shall never be detected experimentally"*.

Only Pontecorvo challenges this opinion. In 1945, while working at the Chalk River Laboratories in Canada, he proposes a remarkable radiochemical method for neutrino's detection.

In the internal report entitled *"On a method for detecting free neutrinos"* [23] he explains his absolutely brilliant idea on how its possible to capture a neutrino and prove its physical reality despite its trifling chance of interacting with anything. He writes: *"It has been currently stated in the literature that an inverse β process produced by neutrinos cannot be observed, due to the low yield. (...) The object of this note is to show that experimental observation of an inverse β process is not out of question and to suggest a method which might make an experimental observation feasible"*.

In the paper he proposes a list of reactions in which a neutrino is absorbed and a nucleus of charge Z±1 is produced. "T*he essential point in this method is that radioactive atoms produced by inverse β-ray process have different chemical properties from the irradiated atoms. Consequently, it is possible (by means of the usual carrier technique) to extract from an irradiated volume of the order of cubic meters the radioactive atoms of known life-time"* [23].

One year later, in a second report entitles *"Inverse β process"* [24], Pontecorvo suggests to use the reaction: $\nu + Cl^{37} \rightarrow Ar^{37} + e^{-}$. The experiment he proposes consists in *"irradiating with neutrinos a large volume of chlorine or carbon tetrachloride for a time of the order of one month, and extracting the radioactive Ar^{37} from such a volume by boiling",* as can be read in the paper. The unstable radioactive argon can be then identified by detecting the 2.8 keV Auger electron emitted in the $Ar^{37} \rightarrow Cl^{37}$ decay by electron capture (34 day half-life).

Pontecorvo refers clearly to this method when, at page 76 of the first notebook, he comments the activities that his group has carried out during 1951 [Fig.14].

In the top-right side of the page he writes the Chlorine-Argon reaction proposed in the Chalk River paper of 1946. Close to the formula, on the left, he writes the distance the neutrinos can travel in matter before interacting, i.e. 10^{16} Km. In writing this huge distance probably Pontecorvo is considering the amount of Chlorine required to detect such an elusive particle. In the page he remarks: *"At the seminar was discussed the* *problem of the detection of free neutrinos,......... The conclusion is that such possibility is not too far from present day facilities. A short report on this subject was written".*

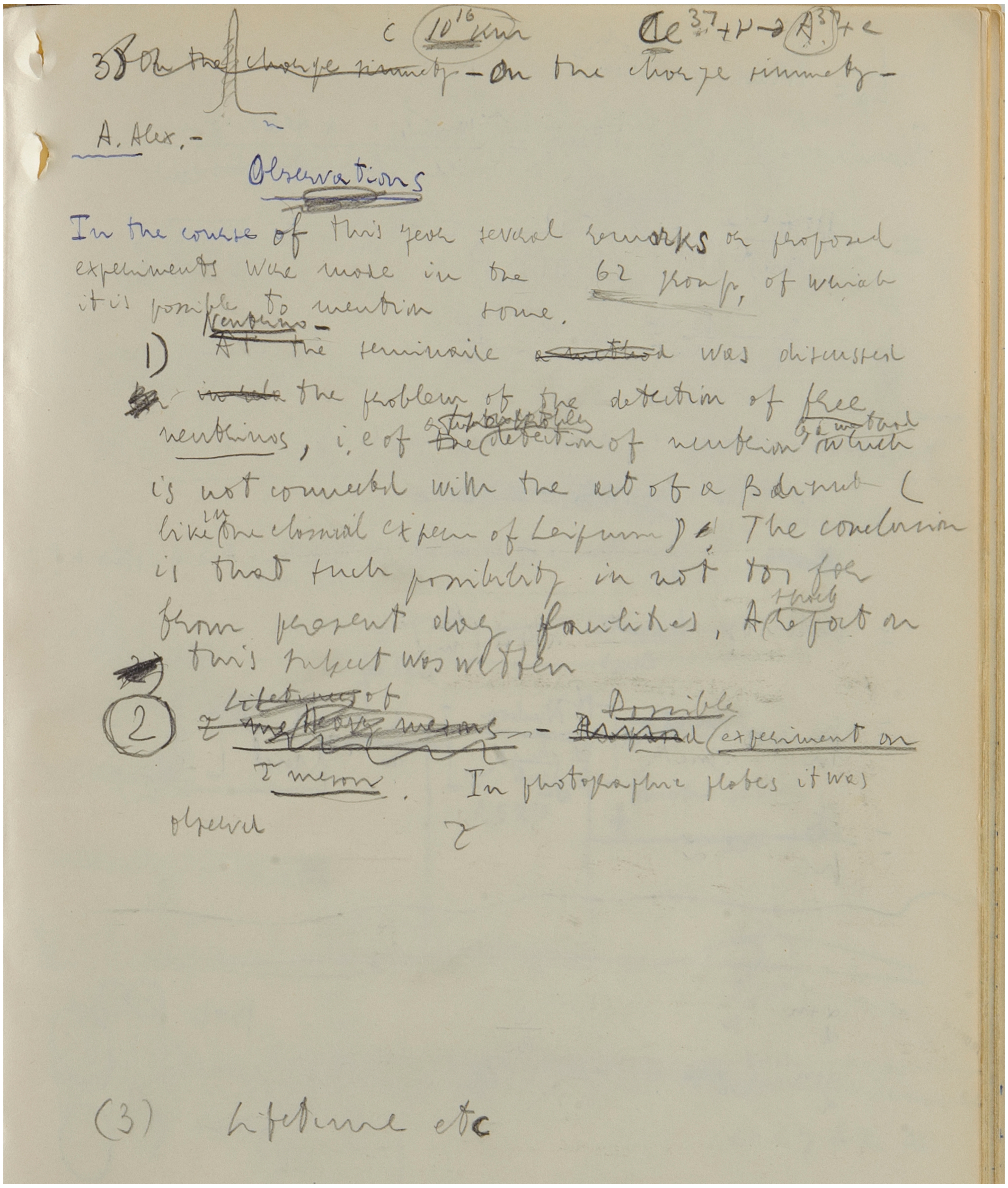


Fig.14 - The Pontecorvo Chlorine-Argon method.

From this note it is evident that Pontecorvo by the end of 1951 is almost sure to be able to detect free neutrinos. It should be really interesting to find the "short report" he refers, to understand how and where he thought to perform this experiment in Russia. Unfortunately, as remarked by the Russian physicist S.S. Gershtein, he could never realize this brilliant idea in the USSR because he had even denied access to any nuclear reactors that he considered to be the most promising source of neutrinos.

The father of neutrino physics

Bruno Pontecorvo can be advisedly considered the father of the modern neutrino physics, one of the first who understood the importance of neutrinos for elementary particle physics and astrophysics.

In 1954, R. Davis used for the first time the Chlorine-Argon method by exposing a 3900 liters tank of Chlorine to the Brookheven nuclear reactor and subsequently an 11,400 liters tank to the most powerful Savannah River reactor, without being able to produce the Chlorine-Argon reaction. This was the first experimental indication that nuclear reactors are source of antineutrinos. But Davis was not the only one who used a nuclear reactor as intense neutrino source, as proposed by Pontecorvo in his paper. One year before, in 1953, also F. Reines and C.L. Cowan Jr., have realized a 300 liters scintillation detector to capture neutrinos from the Hanford reactor. Only few years later, in June 1956, they announced in a telegram sent to Wolfgang Pauli in Zurich, to have unequivocally detected antineutrinos from the fission fragments of the Savannah River reactor. For this discovery, in 1995, Reines was awarded the Nobel Prize (Cowen was dead by that time).

In the Chalk River paper of 1946, Pontecorvo had proposed as neutrino source not only the "pile" but also the Sun. So, twenty years later, Davis developed another experiment based on the Pontecorvo Chlorine-Argon method to detect solar neutrinos, and placed a 378,000 liters tank of perchloroethylene, a commonly used dry-cleaning chemical, in the Homestake Gold Mine in South Dakota. Davis's experiment confirmed that the sun produces neutrinos, but only about one-third of the number of neutrinos predicted by theory were detected. It is the so-called "solar neutrino deficit" predicted by Pontecorvo 10 years before, in the famous article *"Inverse beta processes and nonconservation of lepton charge"* [25]. In this paper Pontecorvo suggests his most remarkable and audacious idea, namely the neutrino oscillations and asserts that the phenomenon *"...will certainly occur, at least, on an astronomic scale".* In 2002 Davis was awarded the Nobel prize in Physics in particular "for the detection of cosmic neutrinos".

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

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

Anyhow Bruno Pontecorvo has given a fundamental contribution to the field of the neutrino physics and in particular to the neutrino oscillation theory. He defended the concept of oscillations in years in which neutrinos were considered massless and so oscillation impossible. Unfortunately he didn't live to see the phenomenon of oscillating neutrinos established as a scientific fact. Afflicted by Parkinson's disease, he died in

Dubna in Autumn 1993. According to his will part of his ashes have been buried in the non-Catholic Cemetery in Rome. On his tombstone it has been engraved the epitaph "$\nu_\mu \neq \nu_e$" as recognition to the scientist who first postulated the existence of of different flavours of neutrinos.

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