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Colloquia: The Legacy of Bruno Pontecorvo

The birth of lepton universality and the second neutrino

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Summary. — Bruno Pontecorvo has given many important contributions to particle physics, two of which were closely related to my work at the beginning of my career. I will discuss them here and I will also describe my first meeting with Bruno in 1973, on the occasion of a visit to Dubna.

1. – Introduction

I met Bruno Pontecorvo in June 1973, on the occasion of my first visit to JINR, Dubna. However, I had become familiar with some of his work on the weak interaction when I was still a physics student at the end of the 1950s, because it was directly related to my thesis subject [1], and later to the first experiments in which I took part [2].

I obtained a degree in physics from the University of Pisa in 1959 under the supervision of Marcello Conversi. The subject of my thesis was the design and feasibility study of an experiment to measure the longitudinal polarisation of neutrons emitted from μ^- capture in nuclei (the purpose of this measurement was the detection of parity violating effects, which had not yet been observed in muon capture). The experiment should have been carried out at the CERN 600 MeV Synchrocyclotron, but it was never done, neither by us nor by other groups in other laboratories. Nevertheless, it was very useful for my initial training in experimental particle physics because it gave me the opportunity of learning the weak interactions and of working hands-on on a variety of experimental techniques. I read the 1947 paper by Pontecorvo explaining the mechanism of muon capture [1]. This important paper will be described in more detail in Section **2**.

While preparing this experiment, at the end of 1959 our group became interested in the study of neutrinoless conversion of negative muons into electrons in muonic atoms. This was one of the so-called forbidden processes, which did not seem to occur despite the absence of any known selection rule forbidding it.

The search for such a process appeared to be experimentally simpler than the measurement of the longitudinal polarisation of neutrons emitted from μ^- capture. We had already built all the beam instrumentation, so we changed subject and designed an experiment to search for ~ 100 MeV electrons emitted from μ^- capture in copper. This was the first experiment in which I took part.

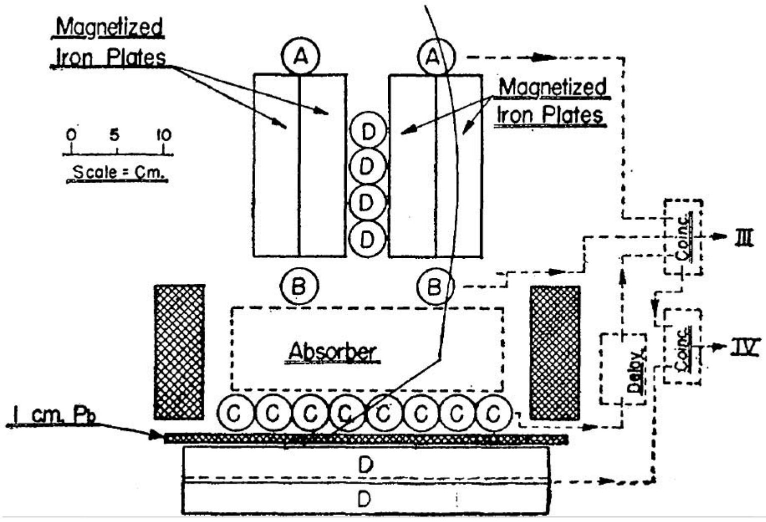

Fig. 1. – The detector used by Conversi, Pancini and Piccioni [7].

While various groups around the world were performing searches for forbidden muon processes with increasing sensitivities, Bruno Pontecorvo published a paper [2] discussing the possible existence of two different neutrinos as a way to explain the absence of forbidden processes, and proposing to use neutrinos produced by proton accelerators to verify this hypothesis. Pontecorvo's paper, and the discovery of the second neutrino, will be discussed in Section **3**.

2. – The birth of lepton universality

In 1935 Yukawa [3] had formulated a theory of nuclear forces based on the exchange of a boson with a mass of the order of 200 electron masses.

This boson, named "meson" or "mesotron", was initially identified with the charged particle discovered in the cosmic radiation in 1937 [4]. It was predicted [5] that negatively charged "mesons" brought to rest in matter would be attracted by the atomic nuclei, form mesonic atoms and, according to Yukawa's theory, quickly undergo nuclear capture releasing their rest energy in the form of nuclear fragments and excitation. Positively charged "mesons", on the contrary, would be repelled by the atomic nuclei and decay to a positron.

To test this behaviour, an experiment was performed in Rome by Conversi, Pancini and Piccioni by stopping cosmic ray "mesons" in a dense absorber after magnetic selection of their charge sign [6,7] (see Fig. 1). Electrons from meson decay were recorded between 1 and 10 μsec after the muon stop signal.

In a first set of measurements using an iron absorber, no decay electron was observed, in agreement with theoretical predictions [5]. However, when a carbon absorber was used, decay electrons were observed with a rate very similar to the rate measured with positive "mesons" [7], in strong disagreement with the theoretical prediction [5]. This measurement demonstrated that cosmic ray "mesons" were not the bosons postulated by Yukawa [3].

Soon after this result became known, Bruno Pontecorvo, then working at the Chalk River Laboratory in Canada, published a paper [1] in which he notices that "the probability ($\sim 10^6 sec^{-1}$) of capture of a bound negative meson is of the order of the probability of ordinary K-capture processes, when allowance is made for the difference in the disintegration energy and the difference in the volumes of the K-shell and of the meson orbit."

There is no attempt to provide a quantitative comparison between the two capture rates in this paper, so it is useful, in my opinion, to provide an order of magnitude estimate of their ratio. An approximate estimate of the phase space ratio between the capture of a bound negative meson and ordinary electron K-capture is given by the squared ratio of the energies released in the two processes: ($\sim$ 100 MeV / $\sim$ 1 MeV)$^2 \approx 10^4$.

This ratio must be further multiplied by the ratio of the overlap probabilities of the meson and electron with the atomic nucleus under the assumption that both processes are due to a point-like interaction. For light nuclei such as Carbon, the overlap probabilities are proportional to the 3^{rd} power of the meson and electron masses, respectively: $(M/m_e)^3 \approx 200^3 = 8 \times 10^6$, where M is the meson mass (this term corresponds to the ratio between the electron and meson K-shell volumes mentioned in Pontecorvo's paper). So, the ratio between the meson and electron capture rates from an atomic K-orbit is as large as $\sim 8 \times 10^{10}$. The intuition that the two processes could be due to the same interaction despite such a large difference between the two rates is really amazing.

On the basis of this intuition, Pontecorvo further writes in the same paper [1]: "We shall consider then the hypothesis that the meson has spin $\frac{1}{2}\hbar$". Thus, at the same time he also proposes that the comic-ray meson might just be a heavier electron. This demonstrates once again Pontecorvo's remarkable imagination.

The cosmic-ray meson is presently named "muon" and denoted as $\mu^\pm$. Yukawa's meson (the pion, π) was discovered in 1947 [8].

The importance of the experiment by Conversi, Pancini and Piccioni [7] was duly acknowledged. For example, in his 1968 Nobel lecture Luis Alvarez wrote [9]: "As a personal opinion, I would suggest that modern particle physics started in the last days of World War II, when a group of young Italians, Conversi, Pancini, and Piccioni, who were hiding from the German occupying forces, initiated a remarkable experiment".

In contrast, Pontecorvo's paper [1], which provided the correct interpretation of those experimental results, was largely ignored. Indeed, in the 1950s the credit for the idea of a Universal Fermi Interaction capable of describing simultaneously β decay, muon capture and muon decay was given to Puppi, who had proposed it in a 1948 paper [10]. This interaction was graphically represented by the so-called "Puppi triangle", as shown in Fig. 2. Obviously, Pontecorvo had proposed two sides of this triangle in his 1947 paper [1]. There is no reference to Pontecorvo's work in Puppi's paper.

3. – The second neutrino

In the 1950s no selection rule was known which would forbid the decay $\mu \rightarrow e + \gamma$. Such a decay was expected to occur as a second-order weak transition, but the decay amplitude could not be calculated because of divergent integrals. Under the assumption that the weak interaction is mediated by the exchange of a charged W boson (see the diagram of Fig. 3), the choice of a cut-off of the order of the W mass resulted in a decay branching ratio, $B_{e\gamma}$, of the order of 10^{-4} [11].

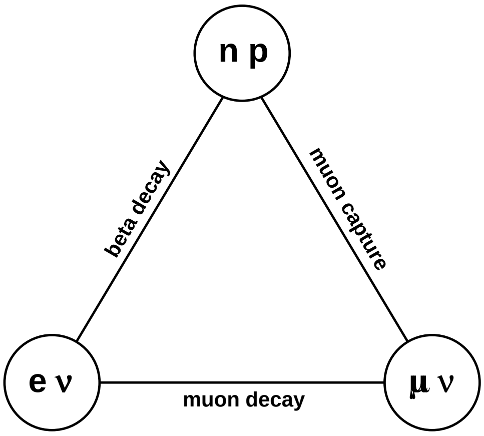

Fig. 2. – Graphic representation of the Universal Fermi Interaction: the Puppi triangle [10].

All searches for $\mu \to e\gamma$ decay had given negative results. The first experiment performed by Hincks and Pontecorvo in 1948 [12] using cosmic muons provided the upper limit $B_{e\gamma} < 10^{-2}$.

In the following years stricter limits were obtained using muon beams from medium-energy proton accelerators. A 1955 experiment at the Nevis synchrocyclotron [13] provided the limit $B_{e\gamma} < 2 \times 10^{-5}$, further improved in 1959 to $B_{e\gamma} < 2.7 \times 10^{-6}$ by an experiment at the CERN 600 MeV synchrocyclotron [14]. By 1962 new experiments with increased sensitivity had further reduced this limit to $B_{e\gamma} < 6 \times 10^{-8}$ [15, 16]. All these results pointed to the existence of a new selection rule forbidding $\mu \to e\gamma$ decay.

However, it was pointed out on very general grounds [17,18] that the $\mu \to e\gamma$ transition amplitude could be very small, or even zero, for the emission of real photons, while being large for virtual photon emission (for the diagram of Fig. 3 this would happen for a specific value of the W magnetic moment [19]). It was important, therefore, to search also for $\mu \to e\gamma$ transitions involving virtual photons before concluding that a new selection rule was needed.

An example of such a transition is the neutrinoless μ^- capture, $\mu^- + (A, Z) \to e^- +$

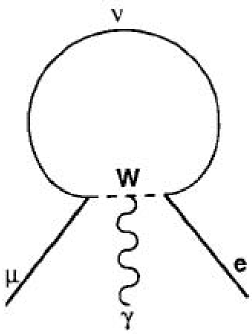

Fig. 3. – Diagram for $\mu \to e\gamma$ decay mediated by the exchange of a charged W boson.

(A, Z), in which the μ^- orbiting around the nucleus undergoes a $\mu \to e\gamma$ transition and the virtual γ is absorbed by the nucleus with or without nuclear excitation. It was shown [17, 18] that for nuclei with Z in the region of 20 to 40 the virtual γ was predominantly absorbed coherently by the nucleus, resulting in the emission of a mono-energetic electron with an energy $E_e \approx 103$ MeV.

A search for neutrinoless μ^- capture in copper had been performed in 1955 at the Nevis syncrocyclotron [20]. No evidence for such a process had been found, providing the upper limit

$$R = \frac{\Gamma(\mu^- + Cu \to e^- + Cu)}{\Gamma(\mu^- + Cu \to \nu + Ni^*)} < 5 \times 10^{-4},$$

for the ratio between neutrinoless and ordinary μ^- capture rate in copper.

A new search for neutrinoless μ^- capture in copper was performed in 1960 at the CERN 600 MeV synchrocyclotron by the Rome group. No signal above background was observed, providing the upper limit $R < 5.9 \times 10^{-6}$ [21]. However, an experiment at the Berkeley syncrocyclotron also carried out in 1960 observed 3 events consistent with this process above a background of 0.23 ± 0.04 events [22]. This gave $R = (4 \pm 3) \times 10^{-6}$, which was statistically consistent with the upper limit obtained by the Rome group, but at the same time provided a strong hint that neutrinoless μ^- capture in copper was indeed occurring.

In view of the importance of the Berkeley result, a new experiment was performed in 1961 at CERN by the Rome group, with several improvements with respect to the previous one. No evidence for neutrinoless μ^- capture in copper was found, providing the upper limit $R < 2.4 \times 10^{-7}$ [23], in disagreement with the Berkeley result. So, by 1962 the need for a new selection rule forbidding $\mu \to e\gamma$ transitions with both real and virtual photons was clear to all people working in the field.

While searches for these forbidden muon processes (as they were named in the late 1950s) were being carried out at various laboratories, in 1959 Pontecorvo published a paper [2], in which he suggested that these processes would not occur if there were two different neutrinos, one associated with the electron (ν_e), and the other associated with the muon (ν_μ). In this case, the transition amplitude described by the diagram of Fig. 3 vanishes because the ν_μ emitted at the $\mu\nu_\mu W$ vertex cannot close the loop at the $e\nu_e W$ vertex.

In the same paper, Pontecorvo proposed also a method to verify this hypothesis using neutrino beams from accelerators. In his words: "To settle the question it is necessary to ascertain experimentally whether a beam of $\bar{\nu}_\mu$ is capable of inducing transitions which can definitely be induced by $\bar{\nu}_e$. From the experimental point of view a beam of muon neutrinos is more attractive than a beam of electron neutrinos for the following reasons. The usual intense source of electron neutrinos are radioactive isotopoes. Their very nature makes them incapable of emitting high energy neutrinos. A good source of muon neutrinos is $\pi - \mu$ decay in which neutrinos are produced with high energies. It would be of interest to use a high energy antineutrino, say $\gg 100$ MeV, since the cross-section for neutrino-induced processes grows rapidly with energy. However, at very high energies the rate of generation of muon neutrinos is reduced due to the relativistic increase of the pion lifetime. We shall discuss, therefore, an experiment for a neutrino with energy < 100 MeV."

Two neutrino-induced processes are considered in that paper [2]:

$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n \tag{1}$$

$$\bar{\nu}_\mu + p \rightarrow e^+ + n \tag{2}$$

Pontecorvo then writes: "Reaction 2, if ν_μ and ν_e are identical, was successfully observed by Reines and Cowan [24], and if $\nu_e \neq \nu_\mu$, the reaction is unobservable. Reaction 1 is a threshold reaction and therefore can never be observed for $\bar{\nu}_\mu$ energies < 100 MeV." To verify these properties, he proposes to dump a proton beam with a kinetic energy of 700 MeV into a dense, high-Z material. In this arrangement most negative pions coming to rest in the dump undergo nuclear absorption, while positive pions decay. In the decay chain initiated by pions at rest ($\pi^+ \rightarrow \mu^+ + \nu$, followed by $\mu^+ \rightarrow e^+ + \bar{\nu} + \nu$) the only $\bar{\nu}$ source is μ^+ decay. These are under threshold for muon production, but if $\nu_e \equiv \nu_\mu$ they can produce positrons, which can be detected using the Reines and Cowan method [24] (measurement of the signal from e^+ annihilation to two photons, followed by the late signal from neutron capture in Cadmium).

However, at the end of the paper Pontecorvo concludes that the beam intensity of existing proton accelerators is not enough to perform the proposed experiment. In his words "To sum up, one could say that an experiment to establish the identity of ν_e and ν_μ, although very difficult, should be seriously considered in the planning of new accelerators".

It is interesting to compare Pontecorvo's paper [2] with the famous paper by Schwartz [25] published few months later. This paper proposes the use of neutrino beams from $\pi \rightarrow \mu$ decay using high-energy pion beams from proton accelerators. The only physics motivation mentioned explicitely in the paper is the investigation of the weak interactions at high energies. Schwartz calculates that "a high-intensity 10 GeV proton machine with a beam intensity of $\sim 10^{15}$ protons/sec may give a counting rate of more than 10^3 per hour" using a detector with a mass of 10^4 kilograms located at a distance of 20 m from the proton target, with a 10 m thick shielding wall in front of the detector. In a note added in proof at the end of this paper [25], the author writes "The author's attention has been called to a somewhat related paper which has just appeared", and gives the reference to Pontecorvo's paper [2].

The main focus of Pontecorvo's paper, namely the two-neutrino problem, is never mentioned by Schwartz [25]. However, it is discussed in a paper by Lee and Yang [26] which follows Schwartz's paper. Here Lee and Yang denote as ν_1 the neutrino emitted in π^+ decay, and as ν_3 the neutrino emitted in β^+ decay of radioactive nuclei. To test the identity of ν_1 and ν_3, they write: "it is necessary to do some kind of capture experiment on the neutrinos or antineutrinos. For example, if ν_1 and ν_3 are different particles, then the reaction $n + \nu_1 \rightarrow p + e^+$ does not occur."

It is well known that the second neutrino (ν_μ) was discovered in 1962 at the Brookhaven AGS [27] using neutrinos from $\pi \rightarrow \mu$ decay following the method proposed by Schwartz [25]. In my opinion, this experiment was made possible by the invention of the spark chamber in 1959 [28] which allowed the construction of a large mass detector providing at the same time good space resolution, and clear muon-electron and muon-pion separation. The Brookhaven experiment used a 10-ton neutrino detector consisting of ten spark chamber modules, each made of nine 2.5 cm thick Aluminium plates. A photograph of this detector is shown in Fig. 4).

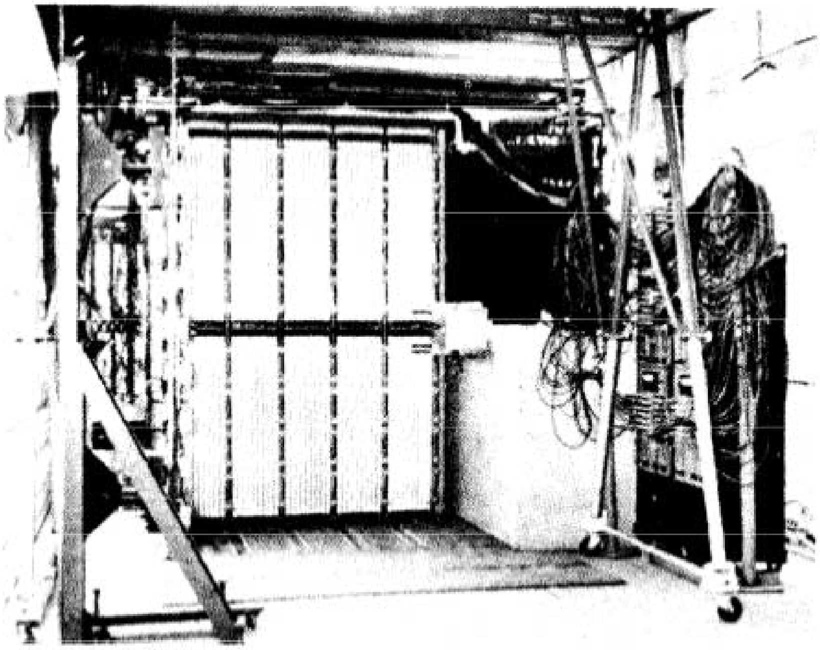

Fig. 4. – The neutrino detector of the AGS experiment at Brookhaven.

Above a momentum threshold of 300 MeV/c 34 muon tracks were observed, but no event consistent with an electron shower. Fig. 5 shows two muon tracks produced by neutrino interactions in the spark chamber plates. For this important result Leon Lederman, Melvin Schwartz and Jack Steinberger were awarded the 1988 Nobel Prize in Physics.

Probably, when he wrote his article [2], Pontecorvo was not aware of spark chambers and gave serious consideration to the only experimental method that had successfully detected neutrinos until then, namely the detection of antineutrinos from a reactor [24]. In addition, as he wrote in a later paper presented at the 1982 Colloquium on the History of Particle Physics [29], in 1958 a proton relativistic cyclotron was being designed at JINR (Dubna) with an energy of 800 MeV and a beam current of $\sim 500\mu A$. Eventually, this accelerator was never built, but beam dump experiments along the lines suggested by Pontecorvo in 1959 [2] were carried out at the end of the last century both at Los Alamos [30] and RAL [31] using new medium energy, high intensity proton accelerators with the purpose of studying neutrino oscillations.

4. – Meeting Bruno Pontecorvo in person

During the second half of June 1973 a meeting on particle physics attended mainly by Russian physicists took place at JINR, Dubna. At that time I was involved in experiments at the CERN Intersecting Storage Rings (ISR), which was the first hadron collider ever built, providing proton-proton collisions at a total centre-of-mass energy of up to 62 GeV. I was ISR physics coordinator, with the task of organizing the day-by-day schedule of the machine in consultation with the users (I had to decide on beam intensities and energies,

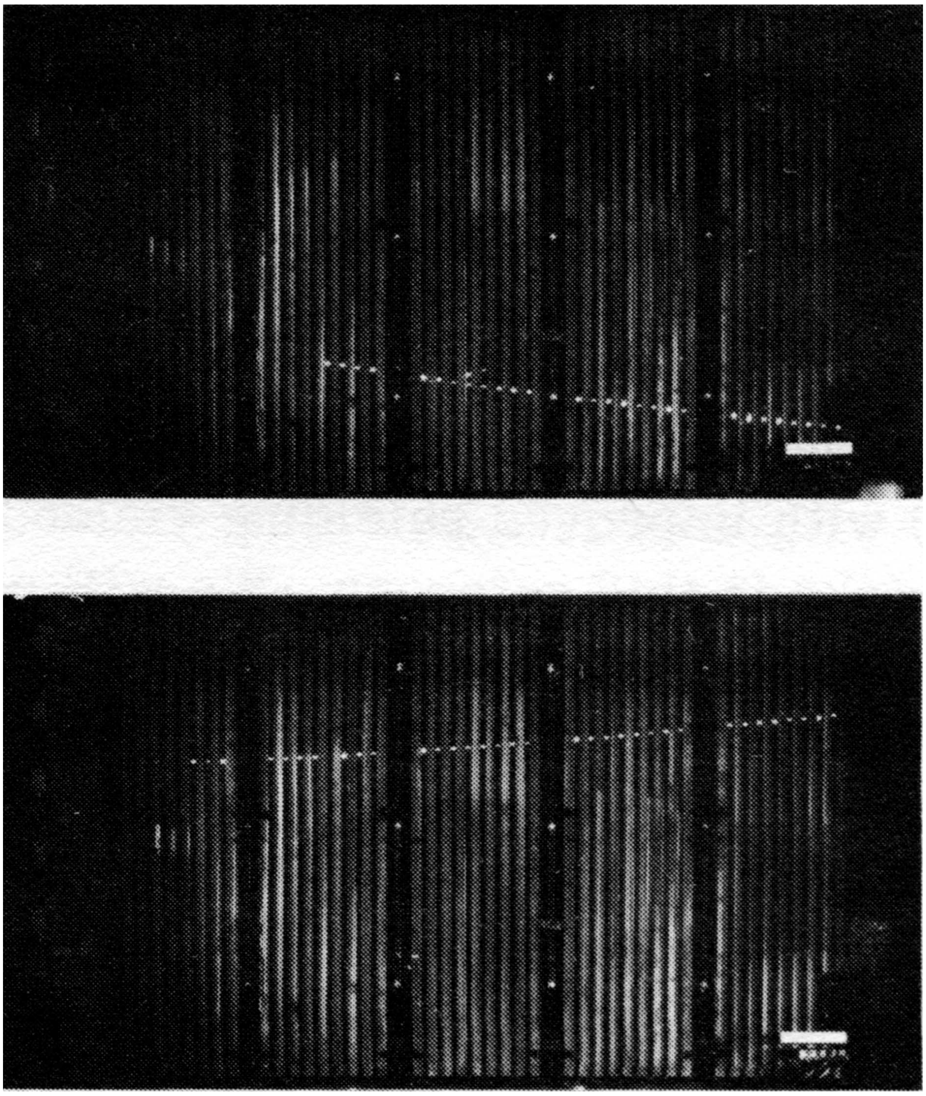

Fig. 5. – Two typical muon tracks from neutrino interactions in the Brookhaven experiment.

length of runs, etc.).

As there was interest at JINR to learn about the ISR and the first physics results obtained with this machine, I was invited to the meeting to lecture on this subject. Bruno Pontecorvo was in the audience and immediately identified me as an Italian, most likely from my accent when speaking English. He approached me during a break and was pleased to learn that I had studied in Pisa, the city where he had lived until he was 18 years old before moving to Rome to study and work with Fermi. He was curious of knowing how Italy and Pisa had evolved since 1950, the year when he moved to the Soviet Union.

When I asked him why, in his opinion, his 1947 paper on the capture of cosmic ray

Fig. 6. – Informal physics discussion during the excursion day to the Moscow Sea near Dubna. Facing Bruno are L. B. Okun' (right) and V. N. Gribov (at the left of L. B. Okun').

mesons by nuclei had been largely ignored (see Section **2**), Bruno's answer was that it was impossible at that time to provide any quantitative verification of his hypothesis that cosmic reay mesons behaved just as heavy electrons, because no measurement of the meson capture in carbon existed yet. Nevertheless, because the cosmic ray meson was definitely not Yukawa's boson, he thought that his ideas should be made known in order to stimulate discussions and further experiments. In the end, he was obviously glad that his intuition had been proven right. I also had the impression that he was pleased that I knew his paper.

Concerning the second neutrino, Bruno said that physicists working on muon decay in the late 1940s and early 1950s never considered the two neutral particles emitted in muon decay as being the same particle, and they often used different notations and names (such as "neutrino" and "neutretto"). He also called my attention to the fact that, in his 1948 paper on the Universal Fermi Interaction [10], Puppi denoted as μ_0 the neutral particle emitted in $\pi^{\pm}$ decay and μ^- capture by nuclei, and wrote muon decay as $\mu^{\pm} \to \mu_0 + e^{\pm} + \nu$.

I enjoyed these discussions from which I learned a lot of physics, but I also enjoyed other activities during that meeting in Dubna. There was an excursion day to the so-called Moscow Sea, an artificial lake created by the construction of a dam near Dubna in the 1930s and connected to the city of Moscow by a man-made canal. There was a recreational area for JINR staff along the coast of this lake, and Bruno invited me to do water skiing with him using one of the two motor-boats available to members of the JINR faculty. It was a very pleasant and warm sunny day, during which we enjoyed open-air activities such as water skiing and swimming, alternating with informal physics discussions in a friendly and relaxed atmosphere. I had a camera with me and took the photo shown in Fig. 6, where Bruno is seen discussing with other eminent Russian physicists, some of them quite informally dressed, while lunch was being prepared.

It was for me an unforgettable day.

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