

# Discovery of muon neutrino

Maria Lorenzon

July 22, 2010

The article I will mainly refer to is “Observation of high-energy neutrino reactions and the existence of two kinds of neutrinos”, written by G. Danby, J-M Gaillard, K. Goulianos, L.M. Lederman, N. Mistry, M. Schwartz and J. Steinberger in June 1962<sup>1</sup>. In the article, they describe the experiment created at the Brookhaven AGS where the interaction of high-energy neutrinos with matter showed the existence of a non-electron type of neutrino. The purpose of the article is indeed showing that the neutrinos obtained by the decay of the pion produce  $\mu$  mesons but do not produce electrons, meaning that these neutrinos are different from those involved in  $\beta$  decay. Moreover, the article provides interesting indications on how to progress in the research of the intermediate boson of the weak interactions.

**Why the need to demonstrate the existence of another type of neutrino?** The idea of the existence of an intermediate boson of the weak force was introduced to avoid the problem of the violation of unitarity. However, the introduction of such an intermediate boson allowed Feinberg<sup>2</sup> to correct the calculation of the branching ratio  $(\mu \rightarrow e + \gamma)/(\mu \rightarrow e + \nu + \bar{\nu})$ , obtaining a value of the order of  $10^{-4}$  under the hypothesis of the existence of only one type of neutrino. This result was also consistent with the experimental absence of the  $\mu \rightarrow e + \gamma$  decay mode. As the branching ratio was measured to be less than  $10^{-8}$ <sup>3</sup>, the existence of only one type of neutrino was called into question, supporting the belief in the existence of two different neutrinos.

---

<sup>1</sup>G. Danby, J-M Gaillard, K. Goulianos, L.M. Lederman, N. Mistry, M. Schwartz and J. Steinberger, *Phys. Rev. Letters* **9**, 36 (1962)

<sup>2</sup>G. Feinberg, *Phys. Rev.* **110**, 1482 (1958)

<sup>3</sup>See for example S. Frankel, J. Halpern, L. Holloway, W. Wales, M. Yearian, O. Chamberlain, A. Lemonick and F.M. Pipkin, *Phys. Rev. Letters* **8**, 123 (1962). The article describes a series of experiments made using spark-chamber techniques to observe the decay of muon into electron and photon. With their equipment they could have observed such a decay with a branching ratio of more than  $10^{-8}$ , but no events were observed.

The experiment is based on the following fact: If only one type of neutrino exists, then neutrino interactions with protons or neutrons should produce as many electrons as muons; On the contrary, if two types of neutrino exist, then there is no reason to expect any electrons. The interactions they considered were the following:

$$\nu + n \rightarrow p + e^-, \quad (1)$$

$$\bar{\nu} + p \rightarrow n + e^+, \quad (2)$$

$$\nu + n \rightarrow p + \mu^-, \quad (3)$$

$$\bar{\nu} + p \rightarrow n + \mu^+. \quad (4)$$

**Is it possible to construct neutrino experiments at accelerators?**

Schwartz<sup>4</sup> showed the feasibility of using high-energy neutrinos to study weak interactions. To produce high-energy neutrinos, he proposed to use high-energy pions which are a natural source of neutrinos:  $\pi^\pm \rightarrow \mu^\pm + (\nu/\bar{\nu})$ . The neutrinos produced in such a way will have a direction which will tend very much towards pion direction and a laboratory energy which will range with equal probability from 0 to 45% of the energy of the pion. The production of the neutrinos could be described in the following way. The source of the pions will be a proton accelerator where the beam is allowed to impinge on a target. The pions produced at the target will then be allowed to travel for some meters. Then they will hit against a shielding wall in front of the detector. Here a part of the pions will decay in high-energy neutrinos. The calculations of Schwartz show that, using protons at about 10 BeV with a beam intensity of about  $10^{15}$  protons/sec, it should be possible to obtain beams of high-energy neutrinos with a counting rate of more than  $10^3$  per hour, considering appropriate distances.

**How was the experiment built?** The authors used the idea presented in the below section to obtain the desired flux of neutrinos: They consider 15-BeV protons and have them strike against a 3-in. thick beryllium target, posed at one end of a straight section 10 ft. long, producing the pions. The flux of particles produced, which moves in the general direction of the detector, strikes a 13.5-m thick iron shield wall at a distance of 21 m from the target. A wall of this thickness can absorb the strongly interacting particles by nuclear interaction (providing an attenuation of the order of  $10^{-24}$  for strongly interacting particles, an attenuation more than sufficient not to alter the results of the experiment) and muons up to 17 BeV by ionization loss.

---

<sup>4</sup>M. Schwartz, *Phys. Rev. Letters* 4, 306 (1960)

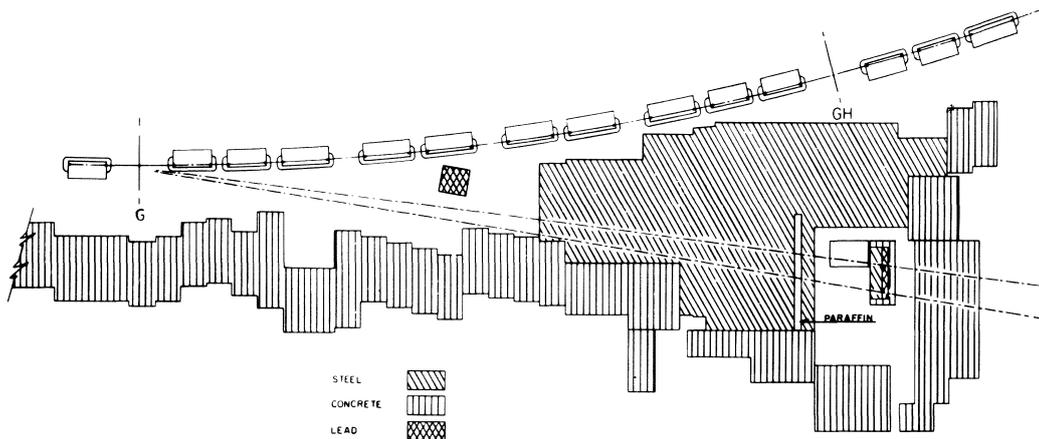


Figure 1: Plan view of AGS neutrino experiment.

The neutrino interactions are then observed in an aluminum spark chamber located behind the shield.

The line of flight of the beam from target to detector creates an angle of  $7.5^\circ$  with respect to the internal proton direction. The energy of the protons is chosen to keep the muons penetrating the shield to a tolerable level.

The spark chamber detector is made by 10 one-ton modules, each one constituted by 9 aluminum plates 44 in.  $\times$  44 in.  $\times$  1 in. thick, separated by  $\frac{3}{8}$ -in. lucite spacers. To reduce the effect of cosmic rays and AGS-produced muons which penetrate the shield, top, back and front anticoincidence sheets are added, for a total of 50 counters. The top and back slabs are shielded against neutrino events. Triggering counters are inserted between adjacent chambers and at the end.

The AGS at 15 BeV works with a repetition period of 1.2 sec. A rapid beam deflector drives the protons onto the target over a period of 20-30  $\mu$ sec. The radiation during this interval has rf structure, because the individual bursts are 20 nsec wide and the separation is 220 nsec wide. A Čerenkov counter exposed to the pions in the neutrino beam provides a train of 30-nsec gates, which is placed in coincidence with the triggering events.

**What was observed?** 113 events were observed, excluding those originated outside the chambers, those which were not originated within a fiducial volume and those of single tracks where the extrapolation of the track backwards for two gaps did not remain within the fiducial volume or where the production angle relative to the neutrino line of flight was more than  $60^\circ$ .

These events were classified as follows:

- 49 short single tracks: If interpreted as muons, they are single tracks

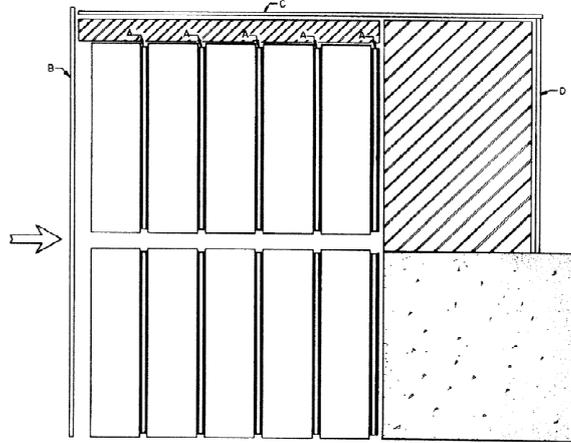


Figure 2: Spark chamber and counter arrangement. A are the triggering slabs, B, C and D are anticoincidence slabs. This is the front view seen by four camera stereo system.

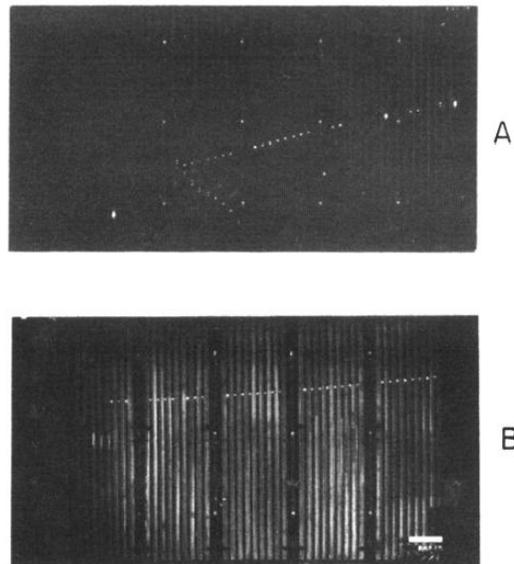


Figure 3: (A) is a vertex event: single muon of  $p_\mu > 500MeV$  and electron-type track; (B) is a single muon event:  $p_\mu > 700MeV$ .

whose visible momentum is less than  $300 \text{ MeV}/c$ . They won't be considered acceptable events, because they include energetic muons that leave the chamber, low-energy neutrino events and the bulk of the neutron produced background.

- 34 single muons of more than  $300 \text{ MeV}/c$ .
- 22 vertex events whose origin is characterized by more than one track. In all of these events an energy release is observable.
- 8 showers. They are not acceptable events, because they are too irregular to be  $\mu$  mesons.

Only the 56 events of the second and third case above were finally considered.

**Can we conclude that two types of neutrino exist?** The decays (1), (2), (3) and (4) are considered again. To conclude that two types of neutrino are highly likely to exist, the authors needed to exclude the decays (1) and (3) from the observed events and to show that the second and fourth decays do not occur with the same rate, as could be expected if the neutrino involved in the decay (2) (which will be indicated with  $\nu_e$ ) and the neutrino involved in the decay (4) (indicated from now on with  $\nu_\mu$ ) were equal.

First of all they exclude that the events observed could be produced by cosmic rays. The background of these simulated neutrino events is measured experimentally by running with the AGS machine off on the same triggering arrangement except for the Čerenkov gating requirement and is of the order of 1 event neutrino-like in 90 cosmic-ray events. Considering that about 440 cosmic-ray tracks are consistent with the observation, they identify  $5 \pm 1$  cosmic-ray events (consistent with the observation of a small asymmetry seen in the projection of angular distributions of single track events) while the other 51 events are unlikely to be the result of cosmic rays.

They also exclude that the events are neutron produced: The origins of the events are uniformly distributed over the fiducial volume, particularly against the last chamber because of the condition that the visible momentum be greater than  $300 \text{ MeV}/c$ , while nuclear and electromagnetic interactions have both a mean free path of a length shorter than 40 cm. This allows the authors to exclude the decays (1) and (3).

The single particles produced are supposed to be muons because there are little or no nuclear interactions. To explain this the authors consider a simplified situation. In a follow-up experiment, it was observed that for the 400-MeV pions the mean free path for nuclear interactions in the chamber was no more than 100 cm of aluminum. Thus, in the initial experiment

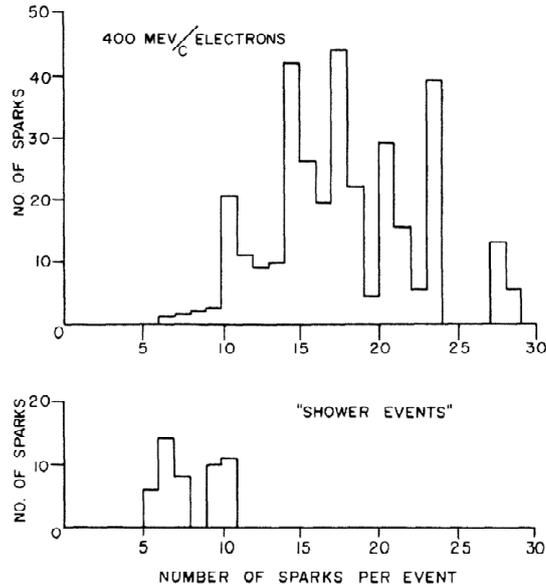


Figure 4: Spark distribution for 400-MeV/c electrons normalized to expected number of showers. Also shown are the shower events.

they should have observed about 8 nuclear interactions, while no nuclear interaction was observed<sup>5</sup>.

The latter consideration allows them to infer that the observed reactions may be due to the decay of pions and kaons. To prove this, in a second background run, the iron was removed from the main shield and was replaced by an equivalent quantity of lead. By changing the conditions this way, the path available for pions was reduced by a factor of 8. The authors observed a reduced rate of events from  $1.46 \pm 0.2$  to  $0.3 \pm 0.2$  per  $10^{16}$  incident protons, which is consistent with the reduction expected for neutrinos produced by the decay of pions or kaons.

Finally they considered only the single track events. Of the 34 single muon events, 5 are considered to be cosmic ray background. If we suppose  $\nu_e = \nu_\mu$ , we expect about 29 electron showers with a mean energy of approximately 400 MeV/c while we observe only 6 candidates of electron showers looking qualitatively very different from the electron events observed at Cosmotron. Later experiments showed that the efficiency of triggering of 400-MeV electrons in the chambers to be 67%. We can see in the plot in figure 4 that the observation is not consistent with the prediction based on the hypothesis that  $\nu_e = \nu_\mu$ . The calculation of the ratio  $(\pi^+ \rightarrow e^+ + \nu)/(\pi^+ \rightarrow \mu^+ + \nu)$  at  $(1.21 \pm 0.07) \times 10^{-4}$ <sup>6</sup>, the results of  $\beta$  decay,  $\mu$  capture and  $\mu$  decay show that

<sup>5</sup>There are five single tracks stopping in the chamber, possibly resulting from one fraction of the neutrinos having been produced with a too small momentum.

<sup>6</sup>*H.L. Anderson, T. Fujii, R.H. Miller and L. Tau, Phys. Rev. 119, 2050 (1960)*

the couplings of single neutrinos with electrons and those of single neutrinos with muons are equal. Hence, we cannot say that the absence of the electrons is caused by the couplings of single neutrinos with electrons. So, the most probable cause of the absence of electron showers is the fact that  $\nu_e \neq \nu_\mu$ .

Note that the presence of one or two electron events was expected from electron-associated neutrinos produced in the decays  $K^+ \rightarrow e^+ + \nu_e + \pi^0$  and  $K_2^0 \rightarrow e^\pm + \nu_e + \pi^\mp$ .

Another consideration can be made<sup>7</sup>. The authors argue that the absence of the electrons events could be due to the fact that the form factors for the heavy-particle currents in the  $e$ -producing reaction is very different from that in the  $\mu$ -producing reaction at a great momentum transfers. However, this obstacle can be avoided thanks to the calculation (see quoted article) which shows that an absolute theoretical lower limit can be established for the rates of the  $e$ -producing reaction without a relative comparison with that of the  $\mu$ -producing reactions. As a matter of fact, using this lower limit we can calculate the number of observed electrons to be greater than 12, with an error of  $\pm 30\%$  due to poor knowledge of the flux of the neutrinos. Even though the error is large, it is not consistent with the observations and, hence, it confirms the hypothesis that  $\nu_e \neq \nu_\mu$ .

**What can be inferred on the  $W$  intermediate boson?** The experiment with high-energy neutrinos could have also been used to investigate the eventual existence of the  $W$  boson, but the poor resolution of the chamber of the Brookhaven experiment obstructed the demonstration of its existence. In the experiment, if intermediate bosons are produced, they should have a mass  $m_W$  smaller than the mass of the proton  $m_p$ . Thanks to the calculations of the cross section of the process  $\nu + p \rightarrow W^+ + \mu^- + p$  showed in figure 5<sup>8</sup>, if  $m_W = 0.6m_p$  they should have observed about 20 events of the process above, while if  $m_W = m_p$  they should have observed 2 events. 5 of the 22 vertex events in the initial experiment are consistent with the existence of a boson: 2 of them could correspond to the decay mode  $W^+ \rightarrow \mu^+ + \nu$ , 1 could be an example of  $W^+ \rightarrow \pi^+ + \pi^- + \pi^+$ , another one could be  $W^+ \rightarrow \pi^+ + \pi^0$  and the last event could be  $W^+ \rightarrow e^+ + \nu$ .

Later calculations<sup>9</sup> introduced a better approximation of the mass of the  $W$  boson considering the number of observed events.

---

<sup>7</sup>This remark was published one year later by the same authors: *G. Danby, J-M Gaillard, K. Goulianos, L.M. Lederman, T.D. Lee, N. Mistry, M. Schwartz and J. Steinberger, Phys. Rev. Letters* 10, 260 (1963)

<sup>8</sup>*T.D. Lee, P. Markestein and C.N. Yang, Phys. Rev. Letters* 7, 429 (1961).

<sup>9</sup>*G. Danby, J-M Gaillard, K. Goulianos, L.M. Lederman, T.D. Lee, N. Mistry, M. Schwartz and J. Steinberger, Phys. Rev. Letters* 10, 260 (1963)

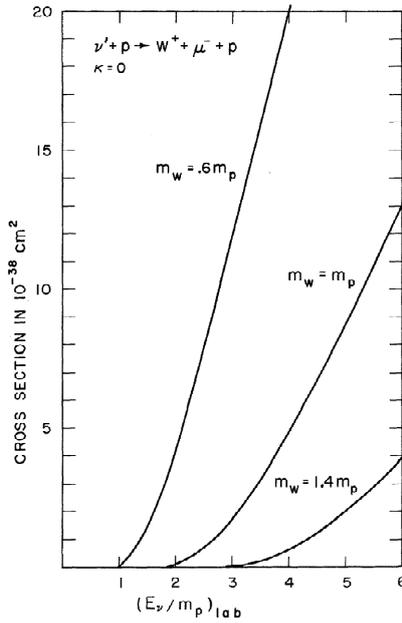


Figure 5: Total production cross section for process  $\nu + p \rightarrow W^+ + \mu^- + p$ .

**What are the implications of this discovery for the development of theories of particle physics?** The 1988 Nobel Prize in physics was awarded to Leon M. Lederman, Melvin Schwartz and Jack Steinberger for their discovery of the muon neutrino. This discovery contributed to compile the list of particles of the Standard Model, including the muon neutrino in the second family of elementary particles. Moreover, the discovery of the muon neutrino helped the discovery of other particles.