THE "TWO NEUTRINO" EXP'T

BROOKHAVEN NATIONAL LAB 1962

CITED IN 1988 FOR:

→ " THE INVENTION OF NEUTRINO BEAMS AS A TOOL FOR STUDYING THE PROPERTIES OF MATTER AND FOR THE DISCOVERY OF TWO KINDS OF NEUTRINOS " ←

NOBEL CITATION

OUTLINE

- HISTORICAL PREAMBLE
  - RADIOACTIVITY
  - β-DECAY
  - PAULI'S HYPOTHESIS
  - FERMI'S THEORY
  - CONSERVATION LAWS
- CAST OF CHARACTERS

?

WHAT HAPPENS TO MISSING ENERGY IN WEAK dec

ENTER, the THEORISTS (1910-1930)

N. BOHR IS READY TO GIVE UP THE CONSERVATION OF ENERGY.

HEISENBERG WAS READY TO ASSUME A NEW TYPE OF DYNAMICS, EVEN A NEW TYPE OF SPACE-TIME DESCRIPTION IN NUCLEAR MATTER.

DIRAC WAS NOT READY TO GIVE UP ENERGY CONSERVATION.

ENTER WOLFGANG PAULI WITH HIS FAMOUS LETTER (DEC. 1930) TO A CONFERENCE ON RADIOACTIVITY, PROPOSING THE EXISTENCE OF A "NEUTRON" OF SPIN 1/2, OBEYING THE PAULI EXCLUSION PRINCIPLE, LIGHT ($m < 0.01\, m_p$)

BOHR AND PAULI ARE SO FAMOUS THAT MANY THEORISTS MARRY BOTH MODELS.
(THE PENALTY FOR BIGAMY IS TWO MOTHERS-IN-LAW!)

IT BEGINS

WOLFGANG PAULI

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dec. 1930
Gloriastr.

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and ^{6}Li nuclei and the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem"[3] of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin $\frac{1}{2}$ and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. – The continuous β-spectrum would then become understandable by the assumption that in β-decay, a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and electron is constant. Now the question that has to be dealt with is which forces act on the neutrons? The most likely model for the neutron seems to me, because of wave mechanical reasons (the details are known by the bearer of these lines), that the neutron at rest is a magnetic dipole of a certain moment μ. The experiments seem to require that the effect of the ionization of such a neutron cannot be larger than that of a γ-ray and then μ should not be larger than $e * 10^{-13}$ cm.

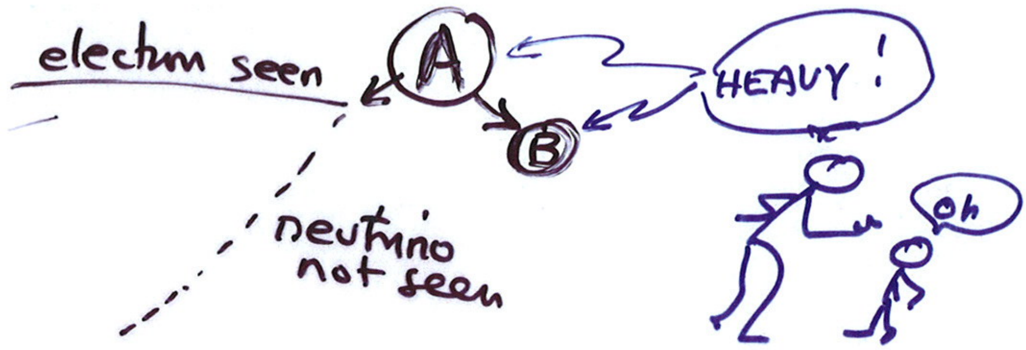
ENRICO FERMI RENAMES THEM "NEUTRINOS" (LITTLE NEUTRAL ONE)

For the moment, however, I do not dare to publish anything on this idea and I put to you, dear Radioactives, the question of what the situation would be if one such neutron were detected experimentally, if it would have a penetrating power similar to, or about 10 times larger than, a γ-ray.

I admit that on a first look my way out might seem to be unlikely, since one would certainly have seen the neutrons by now if they existed. But nothing ventured nothing gained, and the seriousness of the matter with the continuous β-spectrum is illustrated by a quotation of my honored predecessor in office, Mr. Debey, who recently told me in Brussels: "Oh, it is best not to think about it, like the new taxes." Therefore one should earnestly discuss each way of salvation. – So, dear Radioactives, examine and judge it. – Unfortunately I cannot appear in Tübingen personally, since I am indispensable here in Zürich because of a ball on the night of 6/7 December. – With my best regards to you, and also to Mr. Back, your humble servant,

W. Pauli

Increasingly accurate experiments, studying the "β-decay" of radioactive nuclei begin to convince physicists that Pauli's "desparate" idea may be correct.
The neutrino is <u>not</u> detected but one begins to see a "recoil" effect:



1933 ENRICO FERMI PUBLISHES A THEORY OF "β-decay" which uses neutrinos and gives a good ACCOUNT OF THE ELECTRON SPECTRA. ITS A THEORY OF WEAK FORCE REACTIONS

1936 BOHR GIVES UP. HE CONCLUDES THE NEUTRINO HYPOTHESIS AND FERMI'S THEORY ARE COMPLETELY CONSISTENT WITH CONSERVATION LAWS.

Pauli's "neutron" soon to be "neutrino" was slow to be accepted. However, in 1934 Bethe + Peierls first estimated the cross sections of collisions of Pauli's neutrinos with nuclei. It did depend on the new particle's energy.... the neutrinos from β-decay were typically ~ few MeV and

$$\sigma \sim 10^{-44} cm^2$$

The probability of a successful collision rose to ~50% when the thickness of (say) lead was $\lambda \sim 2 \times 10^{14}$ km i.e. ~10 light years. However (!!?☹!) if one has 2 neutrino's need only 5 light-years. Reines + Cowan succeeded in 1955, using the huge flux of neutrino's from a reactor, succeeded in detecting Pauli's neutrino. THEN (1960) T.D. Lee, at Columbia raised the issue of the energy dependence of the weak force.

It had already been shown that neutrinos can be observed and are therefore "real".

THE STORY WE WANT TO RELATE PICKS UP IN 1958-1960 AND (NATURALLY) BEGINS IN THE INTENSIVE DISCUSSIONS OF WEAK FORCES TAKING PLACE AT COLUMBIA UNIVERSITY. THE THEORETICAL FRAME WAS T.D. LEE AND FRANK YANG ALTHOUGH THE COLUMBIA DISCUSSIONS WERE LEAD BY LEE. WE NOTE THAT A PARALLEL DEVELOPMENT IN EUROPE WAS DRIVEN BY THE IMAGINATION AND BRILLIANCE OF BRUNO PONTECORVO.

1959 A TALE OF TWO CRISES

CRISIS #I THE CRISES OF UNOBSERVED REACTIONS

$$\mu^+ \rightarrow e^+ + \gamma \qquad (1)$$

CONSERVES, ENERGY, MOMENTUM, ANGULAR MOMENTUM, PARITY, ELECTRIC CHARGE, SPIN MORAL VIRTUE...

A THEOREM BY GELL-MANN ASSERTED THAT ANY PROCESS WHICH IS NOT FORBIDDEN IS COMPULSORY!

All weak interaction theories predicted that Equ (1) should compete with normal decay of the muon to about 1 part in 10^4. An experiment at Columbia had set a limit:

$$\frac{\mu^+ \rightarrow e^+ + \gamma}{\mu^+ \rightarrow e^+ + \nu + \bar{\nu}} < 10^{-8} \qquad (2)$$

what was disturbing was that $\mu \rightarrow e + \gamma$ can be predicted from a chain of events all of which do happen. E.g:

a) $\mu^+ \rightarrow e^+ + \nu + \bar{\nu}$ — muon decay
b) $e^+ \rightarrow e^+ + \gamma$ — electron radiates
c) $\nu + \bar{\nu} \rightarrow \gamma$ — particle-antipart. annihilation

Net Result: $\mu^+ \rightarrow e^+ + \gamma$

but it DOESN'T HAPPEN!

MORE CONCERN: well-known β-decay:

$$Z \to Z-1 + e^+ + \nu \quad \text{AND}$$
(3)
$$Z \to Z+1 + e^- + \bar{\nu}$$

So when the pion was discovered and studied,

$$\pi^+ \to \mu^+ + \nu$$
(4)
$$\pi^- \to \mu^- + \bar{\nu}$$

It was "known?" (1960) that ν's associated with β-decay were the same particles as associated in pion and muon decay.

In 1958 Feinberg calculated that $\mu \to e + \gamma$ should happen at $\sim 10^{-4}$ if a charged W (intermediate boson) moderated the weak interactions. Since $\mu \to e + \gamma$ was weaker (10^{-8}), therefore W could not exist.

Feinberg did point out that a W might still exist if the neutrinos emitted in (3) with electrons are different from the neutrinos in (4) emitted with muons.

In this case equation c), $\nu + \bar{\nu} \to \gamma$, could not happen.

This would break the logical chain and we would have:

$$\pi^+ \to \mu^+ + \nu_\mu$$
$$\pi^+ \to e^+ + \nu_e \quad \text{AND} \quad \nu_\mu \neq \nu_e$$

The acquisition of subscripts ν_e, ν_μ is the crucial step in resolving crisis #1. The experimental challenge is to determine if

$$\nu_e \neq \nu_\mu$$

CRISIS #2 THE CRISIS OF HIGH ENERGY

~1959 All weak decays take place at "natural" energy of the decay ~ few MeV. The weak interaction, according to the theory should increase as the square of the momentum in a collision – but so far, only the decay energy was available.

Theory says that as the energy of the weak interaction increases as the square of the momentum in the CM, without limit! At Columbia in '59, T.D. Lee insisted that some unknown process must exist to limit the increase of probability with energy. So CRISIS #2: How does the theory get modified? This was known as the unitarity crisis. Typical weak interaction lifetimes are $10^{-6} \sim 10^{-8}$ sec so lets assume 10^{-7} sec is a typical time for something to happen in a weak interaction. If a particle which has a weak interaction is passed through a nucleus how much time is spent in the nucleus?

So we spend 10^{-23} sec in the nucleus. Since 10^{-7} sec is required for something (weak) to happen we need 10^{16} passes for a weak force to work.

In the case of a strongly-interacting particle (pion, proton ...) we need only one pass and we get about this with about 10 cm of lead. i.e. in 10 cm of lead, there is a good chance of a strong collision. <u>BUT</u> for the weak interaction 10^{16} passes requires 10^{17} cm of lead i.e. a thickness of one light year of lead. (Expensive!) But wait → at an energy of 1 GeV, the weak cross section goes up and we need only 10^{12} cm to have a successful collision. (10^{8} miles). THEN Mel Schwartz gets an idea at Columbia (also Bruno Pontecorvo at Dubna)

Schwartz' IDEA

Feasibility of using high-energy neutrinos to study the weak interactions

M. SCHWARTZ, 1960*

For many years, the question to how to investigate the behavior of the weak interactions at high energies has been one of considerable interest. It is the purpose of this note to show that experiments pointed in this direction, though not quite feasible with presently existing equipment, are within the capabilities of present technology and should be possible within the next decade.

We propose the use of high-energy neutrinos as a probe to investigate the weak interactions.

A natural source of high-energy neutrinos are high-energy pions. Such pions will produce neutrinos whose laboratory energy will range with equal probability from zero to 45 percent of the pion energy, and whose direction will tend very much toward the pion direction. For example, 1-BeV/*c* pions will emit neutrinos with an average energy of ~220 MeV in such a way that ~½ of the neutrinos will fall within a cone of half-angle 7°. For orientation purposes, the mean decay distance for such a pion would be 50 meters.

The best-known source of pions is a proton accelerator where the beam is allowed to impinge on a target. Let us assume that we have available a 3-BeV proton beam and 10,000 kilograms of material for sensing a neutrino interaction. We may then estimate the proton flux necessary to produce one interaction per hour with a cross section of σ cm^2. To do this, let us consider the simple setup shown in Fig. 1. Let I be the number of incident protons per unit time, and let, say, $I/10$ charged pions with energy $\geqq 2$ BeV be produced at the target. These pions emerge in a cone of about 45° half-angle, or in about 2 steradians of solid angle. We now let them travel for a distance of 10 meters before hitting a 10-meter shielding wall in front of the detector. Approximately 10 percent of the pions will decay with an average neutrino energy of about 400 Mev. Each square centimeter of detector subtends a solid angle of

*M. Schwartz, Columbia University. Reprinted from *Phys. Rev. Lett.* (1960) Vol. 4, No. 6, pages 306–7. (Submitted February 23, 1960.)

"Late 1959" T. D. Lee leads discussion of possibilities for studying the weak force at high energies.

Schwartz: "That evening a key notion came to me. Perhaps neutrinos from pions decaying in flight could be produced in sufficient numbers to allow us to use them in an experiment. The pions, emerging from the accelerator, would have high energy and some reasonable fraction of the pion energy would be transmitted to the neutrino decay product" (See Eq. 4)

$$(4) \quad \pi \rightarrow \mu + \nu$$

The virtue of using neutrinos to study the energy behavior of the weak force turned out to be profound. The good news is that one can interpose between the intense pion (kaons etc) beam and the detector (now far less than 10^2 cm) a thick wall (~10m thick steel) which would screen out all but neutrinos and, since neutrinos have only the weak force, it is just what we need. Still we needed both lots of neutrinos and lots of target material (we used aluminum rather than lead).

THEN T. D. Lee and F. Yang get another idea. (1960)

THEY INSIST THAT THE UNOBSERVED AND HENCE FORBIDDEN DECAY $\mu \to e + \gamma$ CAN ONLY BE UNDERSTOOD IF, IN EQNS (3) AND (4) REWRITTEN HERE :

$$(3') \quad \pi^+ \to e^+ + \nu_1 \qquad \text{(pion version of (3))}$$

$$(4') \quad \pi^+ \to \mu^+ + \nu_2$$

the neutrinos are different particles i.e.

$$\nu_1 \neq \nu_2$$

it soon became clear that we should identify ν_1 with the production of electrons in weak decays $\nu_1 \equiv \nu_e$ and ditto $\nu_2 \equiv \nu_\mu$

Lee + Yang's general argument is that any mechanism which must act to ward off the unitarity crisis ($\sigma = \lambda^2/4\pi \to 300$ GeV) would permit $\mu \to e + \gamma$ unless $\nu_e \neq \nu_\mu$

THUS BOTH CRISES lead to the question of whether $\nu_e = \nu_\mu$ OR $\nu_e \neq \nu_\mu$.
i.e. TWO (DIFFERENT) NEUTRINO's ?

It was hugely useful that the probability for (4') was $\sim 10^5$ times more probable than (3')

The beam from the accelerator, after screening, would be essentially pure ν_μ

THE muon neutrinos, reacting in our massive (10 ton!) detector would, albeit very rarely, give rise to weak reactions:

$$\bar{\nu}_\mu + p \rightarrow n + \mu^+ \qquad (5)$$

AND (?) $$\bar{\nu}_\mu + p \rightarrow n + e^+ \qquad (6)$$

THE EXPERIMENT THEN:

1) PRODUCE AN INTENSE BEAM OF PIONS, KAONS, OTHER DEBRIS. GIVE THEM A FLIGHT PATH WHICH WOULD ALLOW $\gtrsim 10\%$ OF PIONS, KAONS TO DECAY. WE WILL THEN HAVE A GOOD SAMPLING OF NEUTRINOS FROM PION, etc DECAY. THE MIXED BEAM STRIKES A THICK STEEL WALL. HERE ALL THE PARTICLES (EXCEPT NEUTRINOS) ARE STOPPED OUT OF OUR THICK STEEL WALL, ONLY NEUTRINOS EMERGE AND PASS THROUGH OUR 10 TON DETECTOR. A VERY SMALL FRACTION INTERACT WITH THE ALUMINUM PLATES IN THE 10 TON SPARK CHAMBER.

WE HAVE PREVIOUSLY CALIBRATED OUR DETECTOR TO BE CAPABLE OF DISTINGUISHING MUONS FROM ELECTRONS. IF WE FIND EQUAL NUMBERS OF e's & μ's THEN $\nu_\mu = \nu_e$ [ONE ν]

4. The anticipated branching ratio for $\mu \rightarrow e + \gamma$ should not differ appreciably from 10^{-5}. The fact that the branching ratio was known to be less than 10^{-8} was then *strong evidence* for the two-neutrino hypothesis.

With these observations in mind the experiment became highly motivated toward investigating the question of whether $\nu_\mu = \nu_e$. If there were only one type of neutrino then the theory predicted that there should be equal numbers of muons and electrons produced. If there were two types of neutrinos then the production of electrons and muons should be different. Indeed, if one followed the Lee-Yang argument for the absence of $\mu \rightarrow e + \gamma$ then the muon neutrino should produce *no* electrons at all.

We now come to the design of the experiment. The people involved in the effort were Gordon Danby, Jean-Marc Gaillard, Konstantin Goulianos, Nariman Mistry along with Leon Lederman, Jack Steinberger and myself. The facility used to produce the pions was the newly completed Alternate Gradient Synchrotron (A.G.S.) at the Brookhaven National Laboratory. Although the maximum energy of the accelerator was 30 GeV, it was necessary to run it at 15 GeV in order to minimize the background from energetic muons.

Pions were produced by means of collisions between the internal proton beam and a beryllium target at the end of a 3-meter straight section (see Figure 1). The detector was set at an angle of 7.5° to the proton direction behind a 13.5-meter steel wall made of the deck-plates of a dismantled cruiser. Additional concrete and lead were placed as shown.

To minimize the amount of cosmic ray background it was important to minimize the fraction of time during which the beam was actually hitting the target. Any so-called "events" which occurred outside of that window could then be excluded as not being due to machine induced high energy radiation.

The A.G.S. at 15 GeV operator at a repetition rate of one pulse per 1.2 seconds. The beam RF structure consisted of 20 ns bursts every 220 ns. The beam itself was deflected onto the target over the course of 20-30 μs for each cycle of the machine. Thus, the target was actually being bombarded for only 2×10^{-6} sec. for each second of real time.

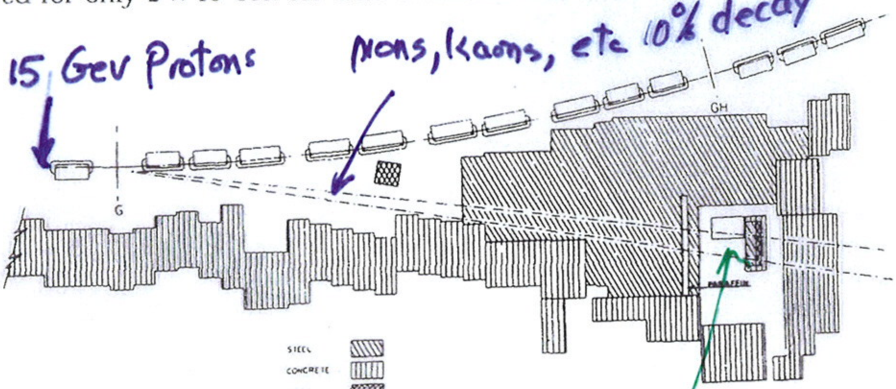


Figure 1. Plan view of the A.G.S. neutrino experiment.

BOTH CRISES ARE ADDRESSED BY 1962 EXPERIMENT OF COLUMBIA-BNL COLLABORATION.

USE NEUTRINO's! THEY HAVE NO CHARGE, ONLY THE WEAK FORCE. IN THE DECAY-IN-FLIGHT OF PIONS PRODUCED BY THE BROOKHAVEN AGS 15 GeV protons: IN THE DECAY OF THE PION

$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu$$

A few GeV pion will give a significant fraction of its energy to the neutrino.

A beam of pions, say π^{+}, emerging from the accelerator will have a mean decay length of ~ 20 m.

Note that these neutrinos are born with muons. Lets give them a subscript: ν_μ

A rare decay ($<10^{-5}$) of pions gave rise to electrons

$$\pi^{+} \rightarrow e^{+} + \nu_e$$

Are the ν_μ and ν_e different particles?

If so

$$\mu^{+} \rightarrow e^{+} + \nu_e + \bar{\nu}_\mu$$

AND $\nu_e + \bar{\nu}_\mu \not\rightarrow \gamma$ EXPLAINING CRISIS I.


Schwartz
Lederman
Danby
Mistry
Gaillard
Goulianos
Steinberger
88-11704
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The Two-Neutrino Experiment

An account of the heroic experiment, involving a 30-billion-volt accelerator, a 10-ton spark chamber and 45 feet of armor plate, that demonstrated that there is not one kind of neutrino but two

by Leon M. Lederman

These days the discovery of a new elementary particle is scarcely news. Physics has been plagued by what seems to be a surfeit of particles for some time. Within the past year, however, a particle has been discovered that may have solved more problems than it has created. An experiment carried out with the 30-billion-electron-volt accelerator at the Brookhaven National Laboratory has demonstrated that there is not, as had been assumed, one variety of the particle known as the neutrino but two. When the Brookhaven accelerator was being designed 10 years ago, many uses were conceived for it, but no one dreamed that it would ever be employed to make neutrinos for experimental observation. Indeed, 10 years ago many investigators were still concerned with the verification of the neutrino's existence. The proof was ultimately supplied by a long series of detailed experiments, climaxed by the direct observation of neutrino-induced reactions in 1956.

Neutrinos are the most impalpable of particles. They have no electric charge, no mass (or none that has yet been measured) and (if it is assumed that they are massless) they travel with the speed of light. They are produced in huge numbers by nuclear processes inside the sun and other stars. Those that encounter the earth pass right through it with ease. Only about one neutrino in every 10 billion (10^{10}) passing through the center of the earth is likely to react with another particle. Obviously a particle that reacted with nothing whatever could never be detected. It would be a fiction. The neutrino is just barely a fact.

Elementary particles reveal their presence by interacting in various ways. Physicists speak of four fundamental kinds of interaction (the modern term for force), which differ markedly in strength. The weakest is gravitation, which is so weak that it becomes manifest only when vast numbers of particles are bound together to form a ponderable body. In the atomic domain, therefore, it can be ignored. In studying the behavior of elementary particles only three forces need to be considered: "strong," electromagnetic and "weak." The relative strengths of the three are roughly in the ratio of 10^{12} to 10^{10} to 1. The strong force is that which holds the particles in the nucleus of the atom together and which is released in nuclear fission and fusion. It has the further property of generating reactions among strongly interacting particles. These are cataclysmic: no sooner are two such particles within "reach" of the strong force than the reaction takes place. The electromagnetic force is that which binds electrons to the atomic nucleus and which underlies all chemical and electric phenomena. For our purposes it is important to note that fast-moving electrically charged particles are slowed down in matter by their continuous interaction with atomic electrons. Weak forces are responsible for the spontaneous decay of unstable—radioactive—nuclei and of elementary particles. Here again to the force or interaction must be attributed the property of inducing transformations among particles. It is believed that all elementary particles are subject to weak-force interactions, although the effects are often obscured by the strong and electromagnetic forces.

All this can be expressed another way by classifying particles according to the interactions in which they can take part. In the present discussion we shall be concerned only with six particles: the proton, pion, neutron, electron, muon and neutrino [*see illustration on page 62*]. Proton and pion take part in all three interactions: strong, electromagnetic and weak. The neutron, being electrically neutral, has only very subtle electromagnetic properties, but it is involved in both strong and weak interactions. Physicists often refer to the three particles—proton, pion and neutron—as "stronglies." The other three—electron, muon and neutrino—are "weaklies." The neutrino, alone among particles, has only weak force. Each of the six particles has a corresponding antiparticle, with an identical set of forces.

One of the earliest forms of nuclear instability to be investigated was that known as beta decay. This is the spontaneous emission of an electron (or its antiparticle, a positron) from an unstable atomic nucleus. When the energies of the emitted electrons were first measured in the 1920's, the results were baffling. It was expected that all the electrons emitted from one kind of nucleus would have the same energy. Instead they had a wide spectrum of energies, ranging downward from some maximum value. How to account for the missing energy?

With deep insight and considerable daring Wolfgang Pauli of Austria suggested in 1931 that the missing energy was being carried off by an undetected particle. The name "neutrino" was soon supplied by Enrico Fermi. Perceiving that the rate of beta decay was enormously slow compared with the rate of other nuclear reactions, Fermi postulated that it represented a new force and developed a theory to describe it. The simplest beta-decay reaction involves the free neutron. Upon ejection from an atomic nucleus the neutron decays spontaneously, yielding a proton and an electron. Again there was missing energy to be accounted for and it was also assigned to the neutrino, or, to be precise, the antineutrino.

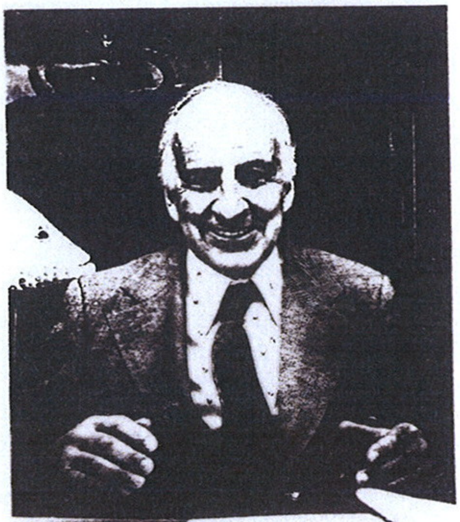
Fermi's theory predicted that it should

Bruno Pontecorvo 1913-1993.

MEET BRUNO PONTECORVO

External correspondents

Bruno Pontecorvo 1913-1993



Academician Bruno Pontecorvo, one of the outstanding physicists of our times, died on 24 September 1993 at the age of 80. He was born on 22 August 1913 in Pisa, Italy. As a student he was noticed by Enrico Fermi and admitted to his world-famous group in 1933, where he participated in the classical investigations of slow neutrons which paved the way for practical applications of nuclear power.

In 1936 Pontecorvo joined Joliot-Curie's group in Paris, again participating in research which laid a foundation for modern nuclear physics, and making significant discoveries of his own. From 1940-42 he worked in the USA, where he devised and introduced a neutron logging technique which is still used in oil prospecting. Then he worked in Canada, the UK (Harwell), and in 1950 moved to the Soviet Union, immediately joining the research at the world's then most powerful synchrocyclotron, which had just been put into operation at Dubna.

Pontecorvo had an impressive ability to generate profound ideas and show how they could be applied. From the middle 1940s he concentrated on weak interaction physics, especially neutrinos. In 1946, while still at Chalk River, he proposed the chlorine-argon method for radiochemical detection of neutrinos which went on to become a powerful tool in the discovery and subsequent study of solar particles.

In 1947, following the discovery of the muon, he proposed the idea of a 'universal' weak interaction for electrons and muons. Ten years later, when he was in residence in his idea to look for muon neutrinos. This involved using high energy accelerators to produce pions, which decay predominantly into muons and neutrinos, and so obtain an artificial beam of high energy neutrinos. This led to the classic experiment at Brookhaven by Leon Lederman, Jack Steinberger and Mel Schwartz which showed that such accelerator-produced neutrinos gave muons rather than electrons. Pontecorvo's suggestions were acknowledged when the trio received their 1988 Nobel physics prize. Later came a third major Pontecorvo neutrino suggestion, the idea of oscillations.

He was also an influential personality and teacher. For some 20 years he headed the elementary particle physics section at Moscow State University. His presence during discussions of new ideas or results created fertile ground for new research challenges. Especially significant was his fruitful contribution to the creative atmosphere and development of research fields at the Joint

IN THE 1958 KIEV/ROCHESTER CONFERENCE AND IN A JETP LETTER, PONTECORVO ILLUMINATES THE LEPTON CONSERVATION PROBLEM AND THE FORBIDDEN REACTION

$$\mu^{+} \not\rightarrow e^{+} + \gamma$$

(THEORY : BR ~ 10^{-4}
EXPT : " ~ 10^{-8})

IN THE PION DECAY

$$\pi^{+} \rightarrow \mu^{+} + \bar{\nu}_{\mu}$$

HE ADDS A SUBSCRIPT TO THE NEUTRINO PRODUCED WITH A MUON AND PROPOSES TO USE THESE NEUTRINOS TO PRODUCE REACTIONS:

$$\bar{\nu}_{\mu} + p \overset{?}{\rightarrow} \mu^{+} + n \quad (1)$$

AND

$$\bar{\nu}_{\mu} + p \overset{?}{\rightarrow} e^{+} + n \quad (2)$$

IF THESE HAPPEN IN ROUGHLY EQUAL RATES THE SUBSCRIPT IS MISLEADING SINCE WE KNOW

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

$$\text{i.e. } \bar{\nu}_{e} \equiv \bar{\nu}_{\mu}$$

BUT

IF (2) IS FORBIDDEN, THEN $\bar{\nu}_{e} \not\equiv \bar{\nu}_{\mu}$

AND

$\mu \rightarrow e + \gamma$ IS SUPPRESSED

i.e IN μ-decay

$$\mu^{+} \rightarrow e^{+} + \nu_{\mu} + \bar{\nu}_{e}$$

& $\nu_{\mu} + \nu_{e}$ <u>cannot</u> annihilate!

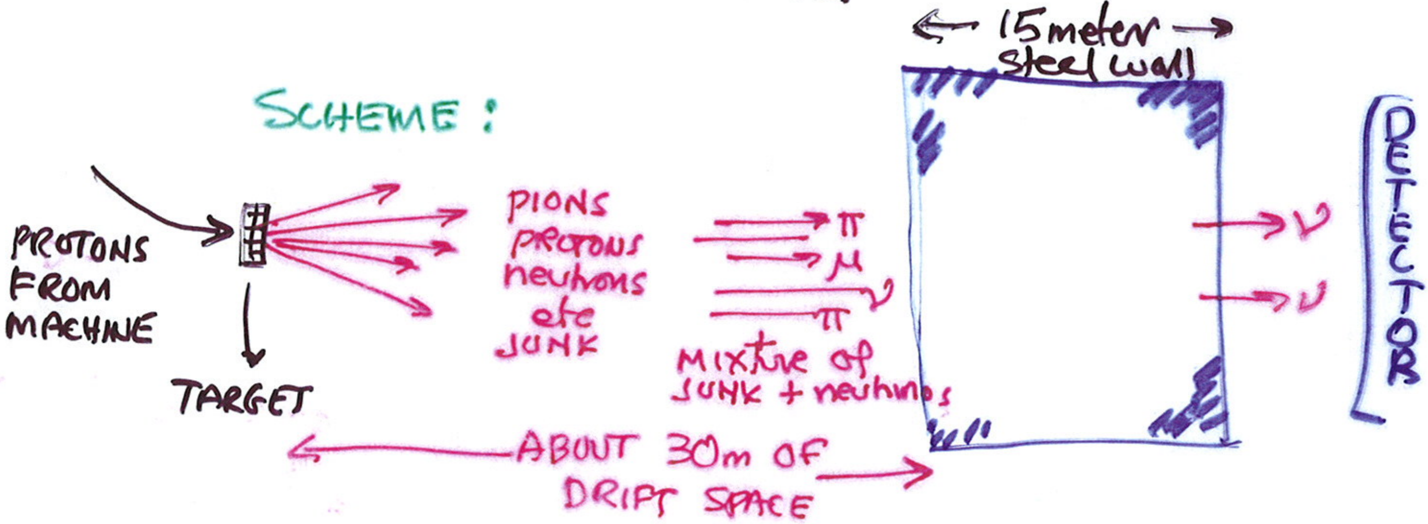
PROBLEM: THE COLLISION PROBABILITY OF NEUTRINO'S IS SMALL.

BUT NOT TO WORRY: IF WE HAVE 10 neutrinos, need only 10 million miles of steel.

In 1960, AT BROOKHAVEN, A NEW PROTON ACCELERATOR COULD PRODUCE 10^{11} (TEN BILLION) PROTONS/sec AND EACH 15 BeV PROTON CAN PRODUCE SEVERAL HIGH ENERGY PIONS.

PIONS LIVE 10^{-8} sec SO IN 30 meters ABOUT 10% DECAY-IN-FLIGHT, PRODUCING A HIGH ENERGY NEUTRINO.

SCHEME:



15 meters (40') OF STEEL STOPS EVERYTHING EXCEPT THE NEUTRINOS (100×10^6 miles of steel)

WE MAKE A PURE NEUTRINO BEAM FROM PIONS: $\pi \to \mu + \nu$

LOGIC OF TWO-NEUTRINO EXP'T

WE SEE IN MANY EXPERIMENTS

1 ● $\mu^- + p^+ \to n^0 + \nu_1$

2 ● $e^- + p^+ \to n^0 + \nu_2$

μ, e universality

$\nu_1 \overset{?}{=} \nu_2$

So it must be that

(1) ● $\nu_1 + n \to \mu^- + p^+$ (1)

(2) ● $\nu_2 + n \to e^- + p^+$ (2)

So get the ν from $\pi \to \mu + \nu$.

IF $\nu_1 = \nu_2 = \nu$ then (1) = (2) { get = no. of e's + μ

IF $\nu_1 \neq \nu_2$

THEN $\pi \to \mu + \nu_1$

1 = μ
2 = e

AND ONLY (1) TAKES PLACE.

SO:
- PRODUCE INTENSE π BEAM ~ 3 GeV
- GIVE π's "TIME" (SPACE) TO DECAY
- FILTER
- LOOK FOR REACTIONS IN A MASSIVE DETECTOR BUT SO INSTRUMENTED THAT μ's + e's CAN BE DISTINGUISHED.
  - $\Rightarrow$ ENERGY MUST BE > 500 MeV
- OPTIMIZE Ω vs PATH-LENGTH

ed for by the one-pion ...
the one-pion-exchange model is valid, ...ce rather strict limits on the angular ... of the $K\overline{K}$ system. Since the G parity ...stem is even, we have[10] $G=(-1)^{L+I}$ ... L is the angular momentum of the ... and I is the isotopic spin. The data ... then suggest the low-energy cross ... $\pi\pi \to K\overline{K}$ is ~2 mb for $I=0$, $L=0$ K ... 0.6 mb for $I=1$, $L=1$ K pairs. Both ...ions drop to low values for energies of ...r more above threshold for the $K\overline{K}$ sys-

...amples of K^+K^- production [reaction ...ed in this experiment were not included ...going analysis. The signature of these ... charged K^+ decay, which is sensitive ...omentum spectrum. Additional bias ...t from the difficulty in distinguishing ...ese events from Σ^+ decays. In our

... Commission and the Wisconsin Alumni Research Foundation.

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OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

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...ourse of an experiment at the Brook-...S, we have observed the interaction ...nergy neutrinos with matter. These ... were produced primarily as the result ...cay of the pion:

$$\pi^{\pm} \to \mu^{\pm} + (\nu/\overline{\nu}). \quad (1)$$

... purpose of this Letter to report some of ...lts of this experiment including (1) dem...on that the neutrinos we have used produce μ mesons but do not produce electrons, a... hence are very likely different from the neutri... involved in β decay and (2) approximate cross sections.

Behavior of cross section as a function of energy. The Fermi theory of weak interactions which works well at low energies implies a cr... section for weak interactions which increases ... phase space. Calculation indicates that weak i...teracting cross sections should be in the neigh...

REVIEW

IN 1959, SCHWARTZ, STIMULATED BY T.D. LEE'S CONCERN WITH THE UNITARITY CRISIS IN THE WEAK FORCE GETS HIS WONDERFUL IDEA: USE NEUTRINOS FROM THE DECAY OF HIGH ENERGY PIONS TO STUDY THE CROSS SECTION $\sigma(\nu p)$.

EVEN THOUGH THE UNOBSERVED $\mu \nrightarrow e\gamma$ IS WIDELY DISCUSSED AT COLUMBIA BY FEINBERG AND LEE, SCHWARTZ' PAPER ONLY DISCUSSES THE HIGH ENERGY BEHAVIOR OF WEAK COLLISIONS — CLEARLY ONLY THE NEUTRINOS AS SCHWARTZ SHOWS CAN DO IT.

PONTECORVO'S PAPER SELECTS THE NEUTRINOS FROM STOPPED PIONS. HE NOTES BRIEFLY THAT DECAY-IN-FLIGHT NEUTRINOS DO HAVE A HIGHER CROSS SECTION BUT DISMISSES THIS IDEA BECAUSE PIONS HAVE A LONGER MFP.

CURIOUSLY, WHAT HE DID WAS TO THROW AWAY A FACTOR OF SEVERAL HUNDRED, NOT ONLY IN $\sigma(E)$ BUT ALSO IN THE FORWARD COLLIMATION OF THE DECAY-IN-FLIGHT NEUTRINOS AND THE GREATER EASE OF DETECTING AND DISTINGUISHING THE HIGH ENERGY COLLISION PRODUCTS: MUONS OR ELECTRONS?

NOTE ALSO THAT SCHWARTZ' LETTER CORRECTLY ESTIMATES AN EXPECTED RATE OF 1 EVENT/HR FOR THE NEW AGS ACCELERATOR NEARING COMPLETION AT BROOKHAVEN. HOWEVER HE COMPLAINS THAT TO DO THE EXPERIMENT RIGHT, HE MUST WAIT FOR A "REALLY HIGH INTENSITY MACHINE."

THE NET RESULT OF THESE IS THAT,
IN 1959, PONTECORVO PROPOSES TO ADDRESS
THE RIGHT QUESTION, $\nu_e \stackrel{?}{=} \nu_\mu$ BUT
WITH A HOPELESS TECHNIQUE AIDED BY
AN INTERESTING ERROR AND SCHWARTZ
ADDRESS A PROBLEM THAT DOESN'T GET
SOLVED UNTIL 1982 AND CARLO FIND THE
W. HOWEVER SCHWARTZ' PROPOSAL IS
THE RIGHT EXPERIMENT TO SOLVE THE
$\nu_\mu \neq \nu_e$ PROBLEM LEADING TO THE HUGE
ACTIVITY IN NEUTRINO PHYSICS.

BUT BRUNO PONTECORVO IS NOT
FINISHED WITH HIS CONTRIBUTIONS — IN 1967
HE PROPOSES NEUTRINO OSCILLATIONS,
HE RELATES A FINITE NEUTRINO MASS
TO CP- NON CONSERVATION AND DISCUSSES
ASTRONOMICAL IMPLICATIONS.

THE REST IS HISTORY.