History of the Neutrino

Discoveries From 1955 to 1962

Lee Grodzins, Professor of Physics Emeritus, M.I.T.

Raymond Davis and Bruno Pontecorvo

- **1946: Pontecorvo suggested the 1st practical method for detecting the neutrino:**
  - **Use an inverse beta decay whose product is a radioactive, inert gas atom. The subsequent beta decay gives a unique signal of the ν.**
    - $\nu + {}_{17}Cl^{37} \rightarrow {}_{18}Ar^{37} + e^-$
    - ${}_{18}Ar^{37} + e^- \rightarrow {}_{17}Cl^{37} + \nu + 3$ **keV x-ray**

My Sources for the History of Parity-Violation Experiments

- I used original papers, review articles and Nobel Prize lectures.
- I also relied extensively on Discovery Stories by C.S. Wu, Richard Garwin and Valentine Telegdi in the γ volume of *Adventures in Experimental Physics*" a short-lived publication created and edited by Bogdan Maglich.

At Least 2 Distinct Neutrinos

1955: **Davis reported his tentative conclusion that Pontecorvo's method did not detect neutrinos from reactors.**

1958: **Davis concluded that the neutrinos from reactors were not detected by the Pontecorvo method.**

- ***The neutrino is not its own antiparticle*.**

The Negative Parity of π^- and π^0

- **William Chinowski and Jack Steinberger reported experimental proofs in 1954 and 1955, respectively, that the π^- and π^0 had negative parity.**
- **In both experiments the π^- beam was stopped in deuterium.**

1954 π^- **(spin 0) + d(spin 1, parity+) → n + n.**

1955 π^- **(spin 0) + d(spin 1, parity+) → n + n +** π^0**.**

➢ ***The angular correlations of the 2 neutrons were measured in coincidence to deduce the parities.***

The 6th Annual Rochester Conference of High Energy Nuclear Physics April 3 to 7, 1956

Session VIII

Theoretical Interpretation of New Particles

C. N. Yang Reported There Were *5* Different Types of K Mesons:

$K_{\pi 3}$ $K_{\pi 2}$ $K_{\mu 2}$ $K_{\mu 3}$ $K_{\mu 3-}$

- Each with almost the same mass, about half that of a nucleon.
- Each with a lifetime of approximately 10^{-10} seconds.

➢ *Yang wrote: "One tries to discover whether we are dealing with Five, Four, Three, Two or One kind of K meson particle".*

The Tau Theta Puzzle

A focus was the in-your-face puzzle of $K_{\mu 3}$ and $K_{\pi 2}$ whose common names were τ^+ and θ^+.

- **τ^+ decays into 3 pions — its parity must be *negative*.**
- **θ^+ decays into 2 pions —its parity must be *positive*.**

➢ ***No one proposed an acceptable solution to this problem.***

Could it be that parity is not conserved?
C. N. Yang's & Richard Feynman's Dialogue

- **Yang stated that it may perhaps be best to keep an open mind on these matters.**
- **Feynman voiced the following question, posed to him by Block: *could it be that θ and τ are different parity states of the same particle* — i.e. that parity is *not conserved* in the K decays?**
- **Feynman added: Does nature have a unique way of defining right- handedness and left-handedness?**
- **Yang replied: We have looked into the matter without arriving at any definite conclusions.**

C. N. Yang
(Yang Chen-Ning)

Richard Feynman

1956: T.D. Lee, C.N. Yang and Chien-Shiung Wu

- The Lee and Yang *Physical Revue* paper showed that parity had never been tested in weak decays; they suggested new experiments that would measure a pseudoscalar:
  - Beta Decay: a “relatively simple” test of the angular distribution of β electrons from spin-oriented nuclei.
  - Meson decay: measure the angular distribution of the electrons with respect to the direction of muons that are emitted from stopped pions.
  - ➢ No one at the time was rushing off to test meson decay.
  - ➢ Wu was already working full-time on testing beta decay.

Chien-Shiung Wu's Parity Experiment

In Wu's *Discovery* story she tells:

- How T.D. Lee came to her little office in the early Spring of 1956, before the Rochester Conference.
- He questioned her about the status of the experimental knowledge of beta decay.
- He then explained the τ-θ puzzle to her and how it led to questioning parity conservation:
  - **If the answer was parity violation, that should be observed in decay asymmetries from polarized beta decaying nuclei.**

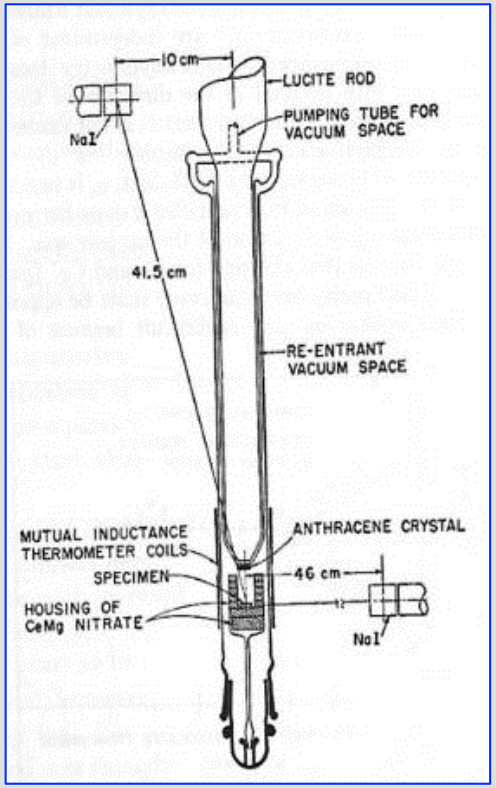
T.D. (Tsung-Dao) Lee

Chien-Shiung Wu

Chien-Shiung Wu's Parity Experiment

Wu was hooked — she wanted to do this fundamental experiment. She was excited to be "challenged by two things which had never been tried before and were difficult."

- **The 1st big challenge was to put the working electron detector inside a cryostat at liquid helium temperature (4.2 °K).**
- **The 2nd big challenge was to keep the beta source located in the thin surface layer and keep the source polarized long enough to obtain meaningful statistics.**



Apparatus

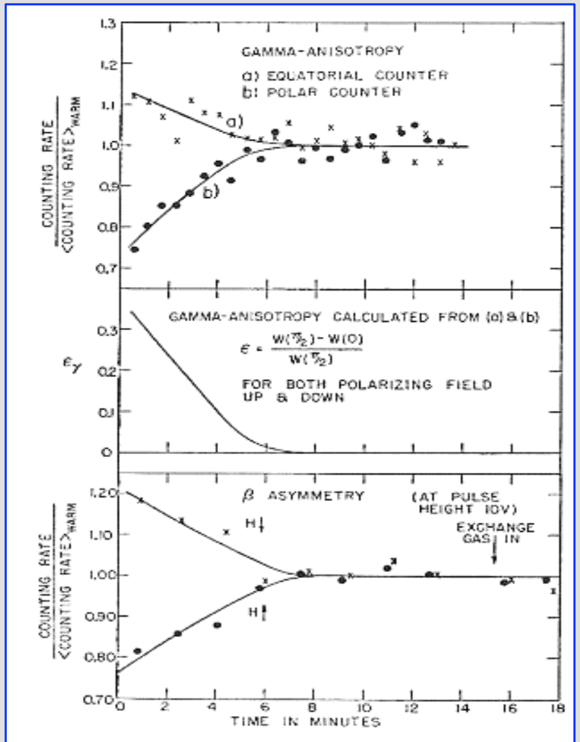


FIG. 2. Gamma anisotropy and beta asymmetry for polarizing field pointing up and pointing down.

Results

Leon Lederman's Regrets

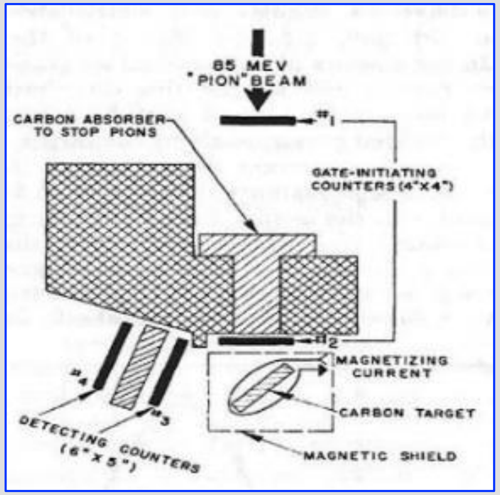
- **Wu reported her results on December 28, 1956, at a weekly Friday luncheon of colleagues.**
- **Lederman, a leading experimentalist of pion and muon physics, was at the luncheon. Over the past summer he had considered investigating the $\pi - \mu - \nu$ chain, but decided that the effect was too difficult to measure.**
- **Driving home he realized that the effect would be large and that the experiment would be easy to do with the apparatus was *already in place* at the Nevis Laboratory.**
  - ***Lederman said to himself, "Oh, the Lost Fame and Fortune!"***

Leon Lederman

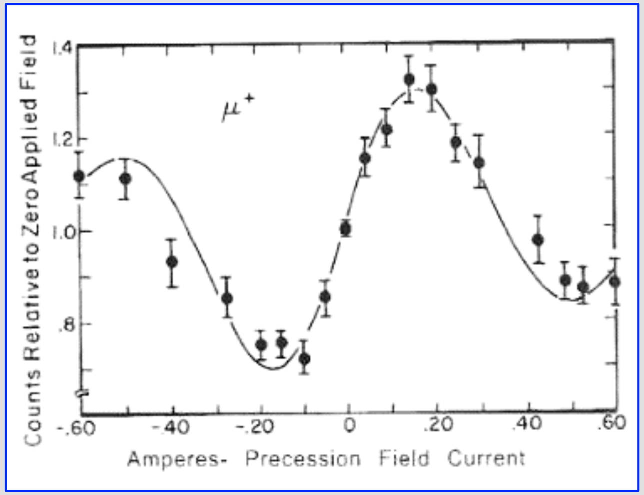
...Later the Same Day, Friday, December 28, 1956

- Lederman told the news of Wu's results to his friend, Richard Garwin — and told Garwin his ideas for testing parity in the $\pi - \mu - \nu$ chain.
- Garwin suggested that they meet that evening at the Nevis accelerator.
- Garwin proposed a new experiment: they would *rotate the muon magnetic moment*, keeping the electron detector at a fixed angle.
- Garwin quickly kluged together a working apparatus and they ran the experiment that evening:
  - ➢ The Initial results were inconsistent but encouraging.
  - ➢ *Their next run 3 days later, using an improved apparatus, produced a 22 δ effect!*

Richard Garwin



Experimental Apparatus

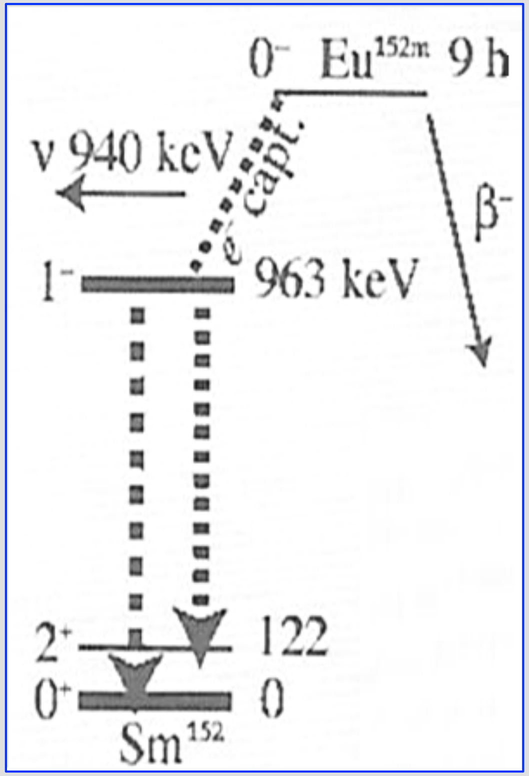


Data

1957: Measuring the Helicity of the Neutrino

To directly measure a neutrino's helicity:

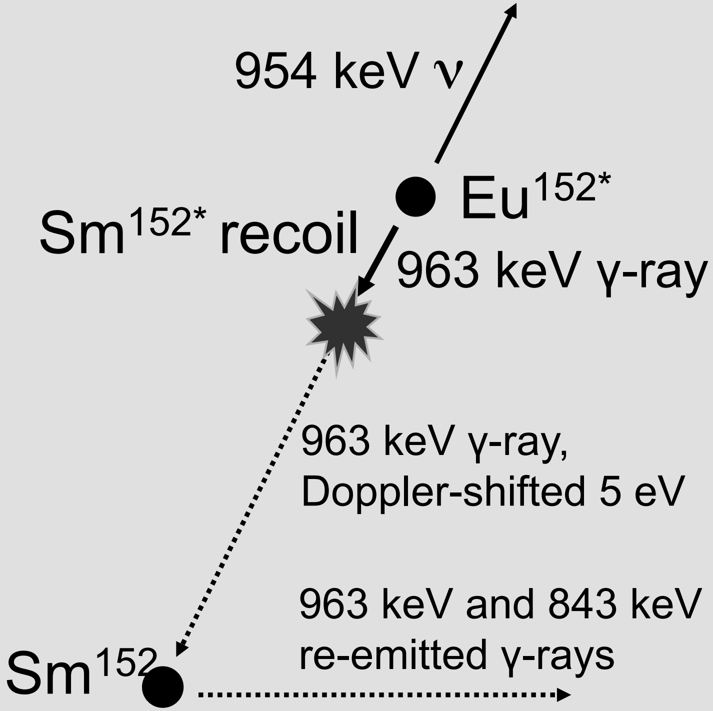
- **It is necessary to *transfer* that helicity to a radiation whose helicity can be measured by some established technique.**
- **In the Goldhaber, Grodzins, Sunyar experiment, the helicity of neutrinos emitted in K-electron capture was transferred to a gamma-ray emitted in the direction of the recoiling nucleus.**

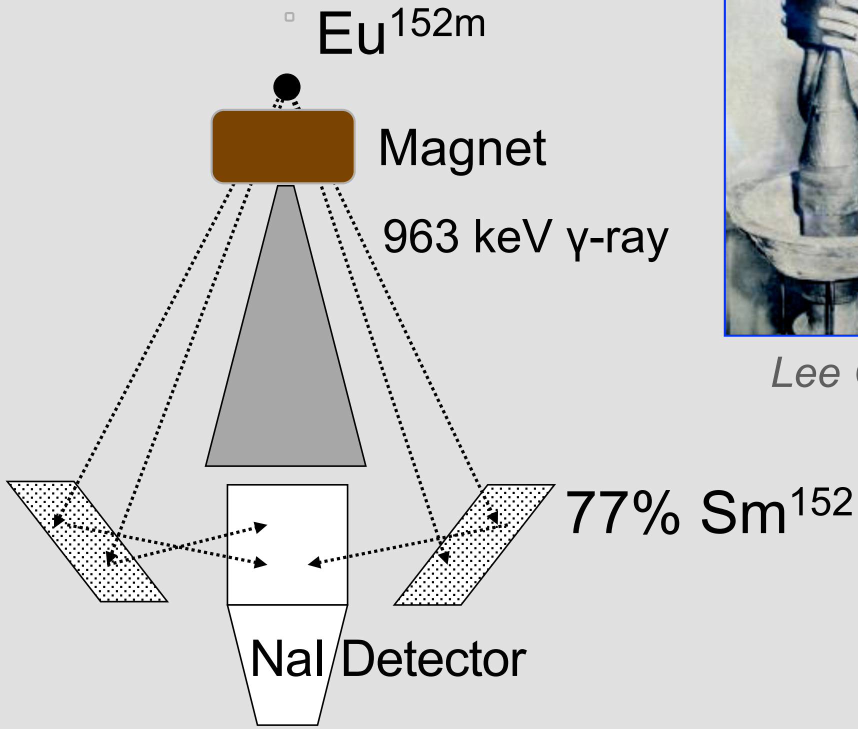


Telegdi's Ideal Decay Properties

1. K-capture, so that the final state of the decay is 2-bodied.
2. The final state of the decay must be to an eigenstate that decays directly to the ground state of a stable nucleus.
3. The neutrino's energy must be at least equal to the energy of the gamma-ray emitting state.
4. The state must decay before the recoiling nucleus collides.
5. The ideal spin-parity sequence is **$0^- - 1^- - 0^+$**
   - **The ^{152m}Eu decay scheme satisfied these plus the other 5 less-critical Telegdi properties for measuring the neutrino's helicity.**
   - **No one has found another decay scheme that does.**

Neutrino Helicity Experiment





Lee Grodzins

Results from the Published Paper

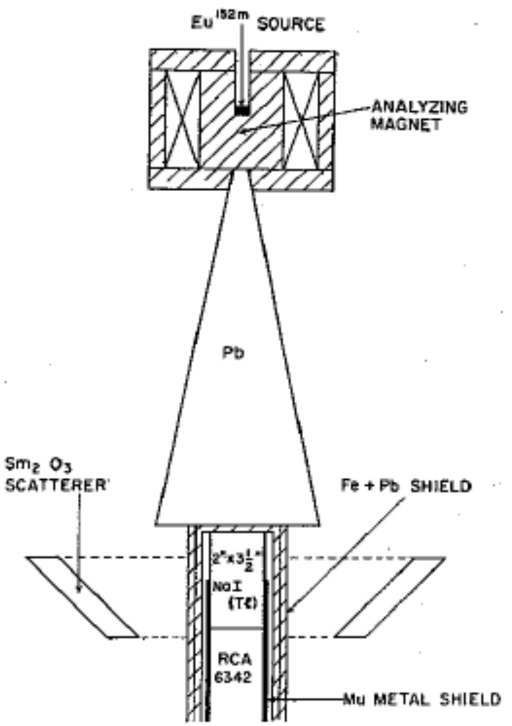


Fig. 6. Schematical arrangement of neutrino helicity experiment. (From Goldhaber *et al.*[1])

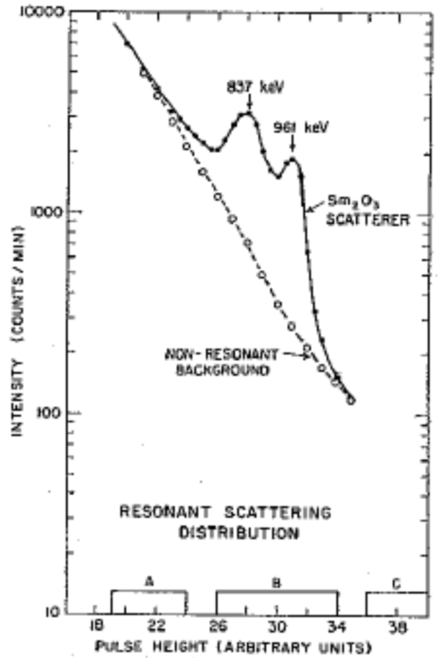
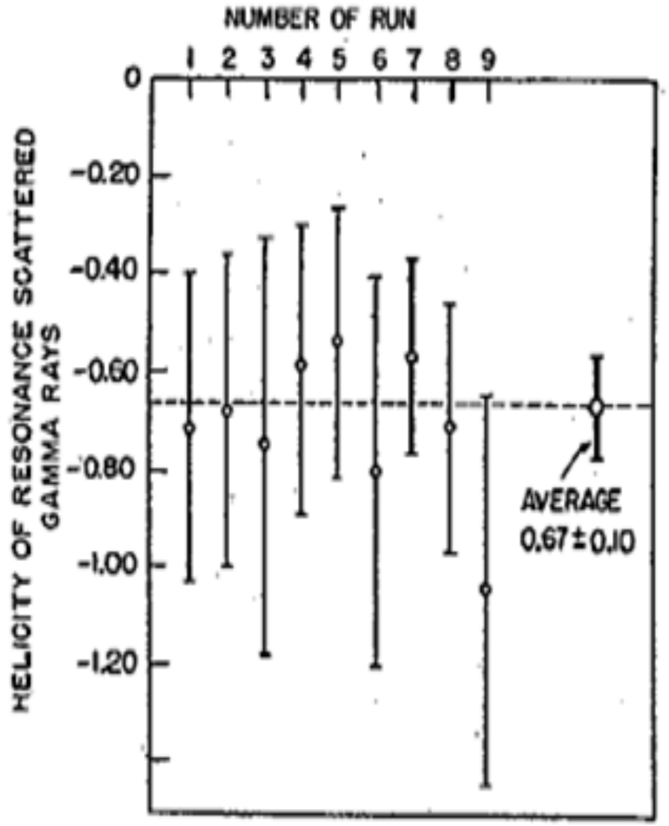


Fig. 7. Distribution of resonant scattered γ-rays of ^{152m}Eu. Taken with arrangement shown in Fig. 6. (From Goldhaber *et al.*[1])



At Left: Apparatus *At Right: Distribution of Resonant Scattered γ-rays*

Results

The Neutrino Emitted in Positron Emission or Electron Capture Has Negative Helicity

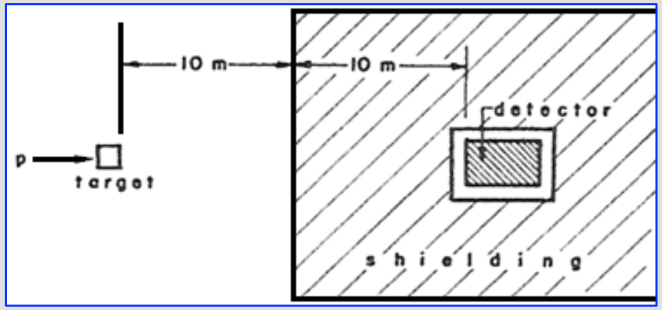
- This result settled the controversy over the nature of weak-interaction currents.
- Beta decay proceeds via axial vector and vector modes.

Maurice Goldhaber

1959: Making Beams of Neutrinos

- In late 1959 a Research Fellow at Columbia University, Melvin Schwartz, attended a coffee-hour discussion led by T.D. Lee about investigations of weak interactions at high energy — all these interactions would produce neutrinos.
- The key ideas to make a neutrino beam in order to directly make these investigations came to Schwartz that evening:
  - High-energy ν_μ's, produced in pion production by high energy protons tend to go in the pion direction.
  - Shield the experiment so that *only* the ν_μ's can penetrate to the detector.
  - Place the system at least 10 m from the proton target so that at least 10% of the pions have decayed.

Melvin Schwartz



Apparatus

Is ν_μ Different from ν_e?

- Schwartz' *Physical Review* Letter was followed by the Lee and Yang Letter on what could be learned from experiments using a neutrino beam.
  - Of 1st importance was to test whether ν_μ differed from ν_e
- Only when Schwarz' paper was in proof did he discover that Pontecorvo had published an *earlier* paper with similar ideas for creating neutrino beams and with similar ideas for neutrino-beam experiments to those proposed by Lee and Yang.
- Schwartz and Pontecorvo were both initially pessimistic about the ability of accelerators then in use to produce useful neutrino beams — each had independently concluded that generating useful neutrino beams would require larger, future accelerators then under construction or being planned.

Bruno Pontecorvo

Lederman and Jack Steinberger then joined Schwartz and Designed a Usable Neutrino Beam

- That initial pessimism was short-lived: then newly-developed spark chambers markedly improved detection capability.
- Lederman, Steinberger and Schwartz proceeded to design and implement a neutrino beam at the AGS accelerator.
- A pion beam was created by 15 GeV protons on Be.
- The pions decayed in the 21 m flight path into a dominant ν_μ beam.

Jack Steinberger

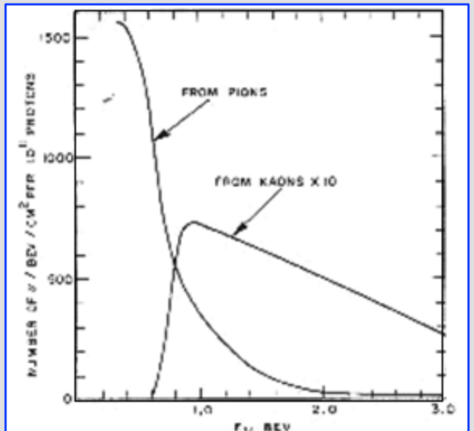
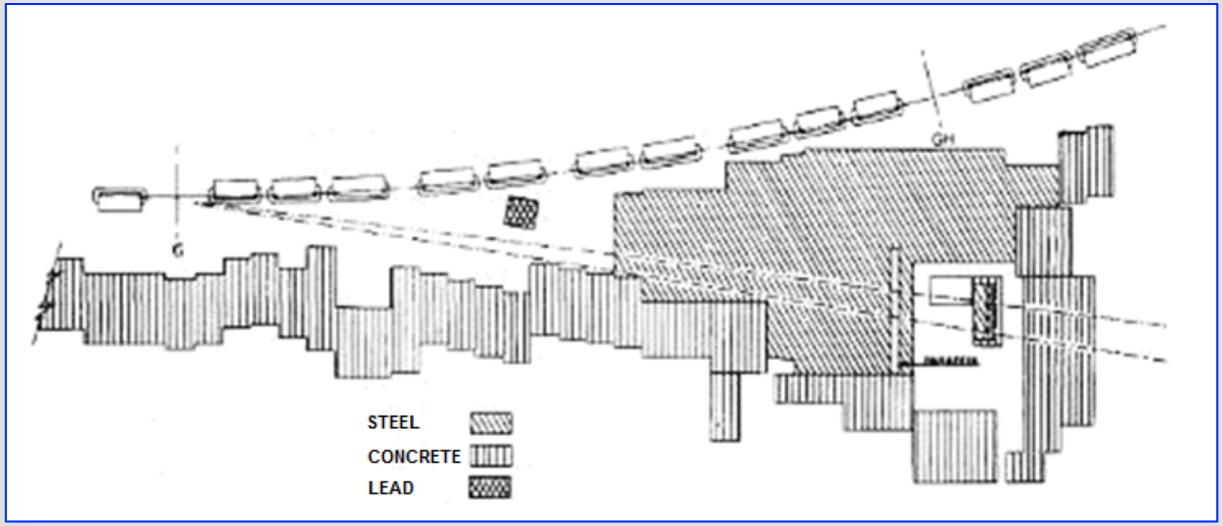


FIG. 2. Energy spectrum of neutrinos expected in the arrangement of Fig. 1 for 15-BeV protons on Be.

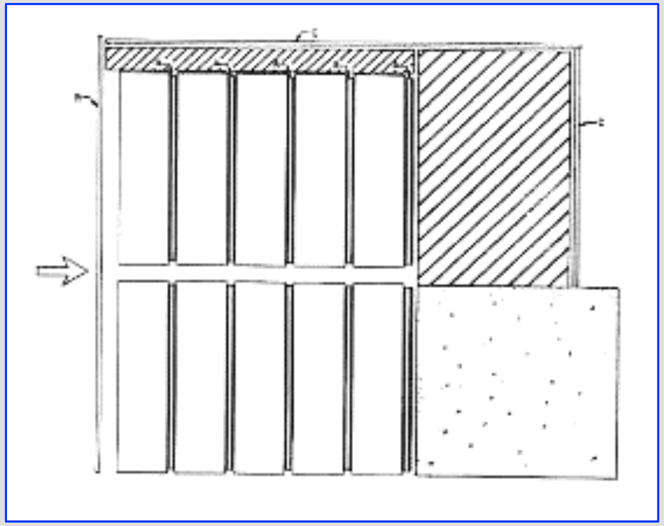
Energy Spectrum of the Neutrinos

Neutrino Beam and Spark Chamber Detector

- **Neutrinos are the *only* beam particles that can penetrate the 13.5 meters of iron that surround the 10 one-ton modules of aluminum spark chambers.**



Plan View of the AGS Neutrino Experiment



Spark Chamber Detectors

Results Demonstrated 2 Types of Neutrinos: ν_μ and ν_e (and antineutrinos $\bar{\nu}_\mu$ and $\bar{\nu}_e$) — *Parity is Not Conserved in Weak Decay*

- Data was subjected to multiple criteria in order to ensure that muons were being counted and that electrons would be detected if they were present.
- Final results were as follows:
  - 34 single muon events were detected from 3.48×10^{16} circulating protons.
  - No certified electrons were observed.

Thank You!