Physics 56400

Introduction to Elementary Particle Physics I

Now in PowerPoint!

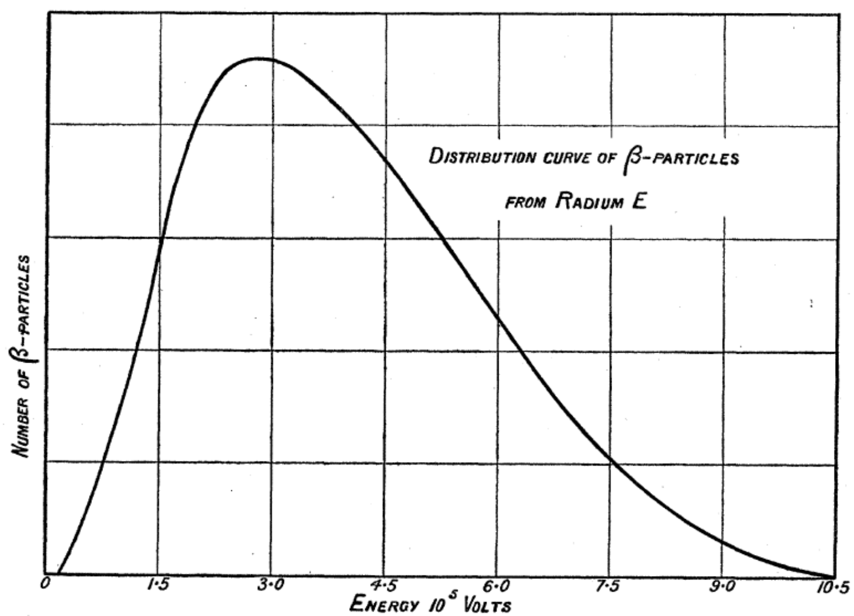
Lecture 24

Fall 2018 Semester

Prof. Matthew Jones

Neutrino Physics

- Early evidence for neutrinos:
  - Continuous spectrum of beta energies
  - Angular momentum conservation arguments
  - Proposed by Pauli in 1930



$$^{210}Bi \rightarrow {}^{210}Po + \beta^{-} + ???$$

Pauli's Neutrino Hypothesis

Original - Photocopie of PLC 0393
Abschrift/15.12.56 FN

Offener Brief an die Gruppe der Radioaktiven bei der Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

Nun handelt es sich weiter darum, welche Kräfte auf die Neutronen wirken. Das wahrscheinlichste Modell für das Neutron scheint mir aus wellenmechanischen Gründen (näheres weiss der Ueberbringer dieser Zeilen) dieses zu sein, dass das ruhende Neutron ein magnetischer Dipol von einem gewissen Moment μ ist. Die Experimente verlangen wohl, dass die ionisierende Wirkung eines solchen Neutrons nicht grösser sein kann, als die eines gamma-Strahls und darf dann μ wohl nicht grösser sein als $e \cdot (10^{-13}$ cm).

Ich traue mich vorläufig aber nicht, etwas über diese Idee zu publizieren und wende mich erst vertrauensvoll an Euch, liebe Radioaktive, mit der Frage, wie es um den experimentellen Nachweis eines solchen Neutrons stände, wenn dieses ein ebensolches oder etwa 10mal grösseres Durchdringungsvermögen besitzen würde, wie ein gamma-Strahl.

Ich gebe zu, dass mein Ausweg vielleicht von vornherein wenig wahrscheinlich erscheinen wird, weil man die Neutronen, wenn sie existieren, wohl schon längst gesehen hätte. Aber nur wer wagt, gewinnt und der Ernst der Situation beim kontinuierliche beta-Spektrum wird durch einen Ausspruch meines verehrten Vorgängers im Amte, Herrn Debye, beleuchtet, der mir kürzlich in Brüssel gesagt hat: "O, daran soll man am besten gar nicht denken, sowie an die neuen Steuern." Darum soll man jeden Weg zur Rettung ernstlich diskutieren.- Also, liebe Radioaktive, prüfet, und richtet.- Leider kann ich nicht persönlich in Tübingen erscheinen, da ich infolge eines in der Nacht vom 6. zum 7 Dez. in Zürich stattfindenden Balles hier unabkömmlich bin.- Mit vielen Grüssen an Euch, sowie an Herrn Back, Euer untertänigster Diener

gez. W. Pauli

Dear Radioactive Ladies and Gentlemen,

…

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 mass. - The continuous beta spectrum would then make sense with the assumption that in beta decay, in addition to the electron, a neutron is emitted such that the sum of the energies of neutron and electron is constant.

…

I admit that my remedy may seem almost improbable because one probably would have seen those neutrons, if they exist, for a long time.

…

Unfortunately, I cannot personally appear in Tübingen since I am indispensable here in Zürich because of a ball on the night from December 6 to 7.

…

signed W. Pauli

Neutrino Mass

E. Fermi, Z. Phys. **88** (1934) 161

7. Die Masse des Neutrinos.

Durch die Übergangswahrscheinlichkeit (32) ist die Form des kontinuierlichen β-Spektrums bestimmt. Wir wollen zuerst diskutieren, wie diese Form von der Ruhemasse μ des Neutrinos abhängt, um von einem Vergleich mit den empirischen Kurven diese Konstante zu bestimmen. Die Masse μ ist in dem Faktor p_σ^2/v_σ enthalten. Die Abhängigkeit der Form der Energieverteilungskurve von μ ist am meisten ausgeprägt in der Nähe des Endpunktes der Verteilungskurve. Ist E_0 die Grenzenergie der β-Strahlen, so sieht man ohne Schwierigkeit, daß die Verteilungskurve für Energien E in der Nähe von E_0 bis auf einen von E unabhängigen Faktor sich wie

$$\frac{p_\sigma^2}{v_\sigma} = \frac{1}{c^3}(\mu c^2 + E_0 - E)\sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)} \qquad (36)$$

verhält.

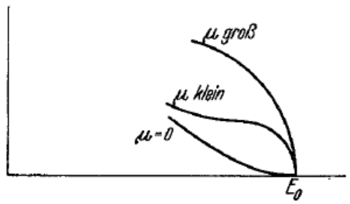


Fig. 1.

In der Fig. 1 ist das Ende der Verteilungskurve für $\mu = 0$ und für einen kleinen und einen großen Wert von μ gezeichnet. Die größte Ähnlichkeit mit den empirischen Kurven zeigt die theoretische Kurve für $\mu = 0$.

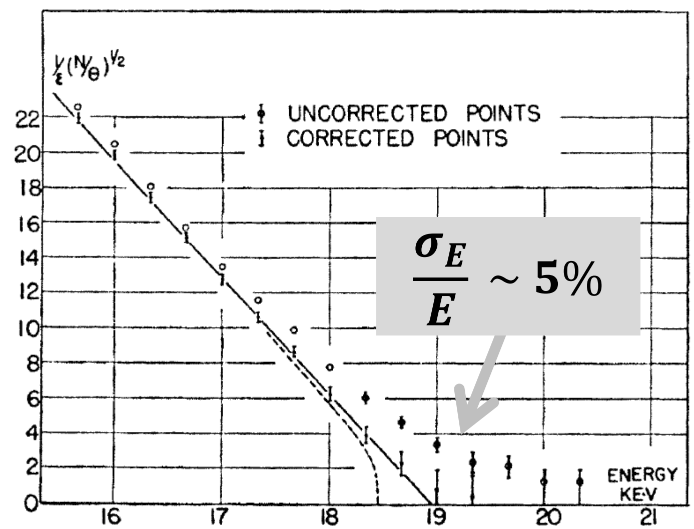
The shape of β energy spectrum near the endpoint is sensitive to the neutrino mass.

Hanna & Pontecorvo,
Phys. Rev. **75**, 983 (1949)

The β-Spectrum of H^3

G. C. Hanna and B. Pontecorvo
Chalk River Laboratory, National Research Council of Canada, Chalk River, Ontario, Canada

January 28, 1949



$$\frac{\sigma_E}{E} \sim 5\%$$

Fig. 2. "Kurie" plot of the end of the H^3 spectrum. The theoretical curve (shown dotted) corresponding to a finite neutrino mass of 500 ev (or 1 kev —see text) has been included for comparison.

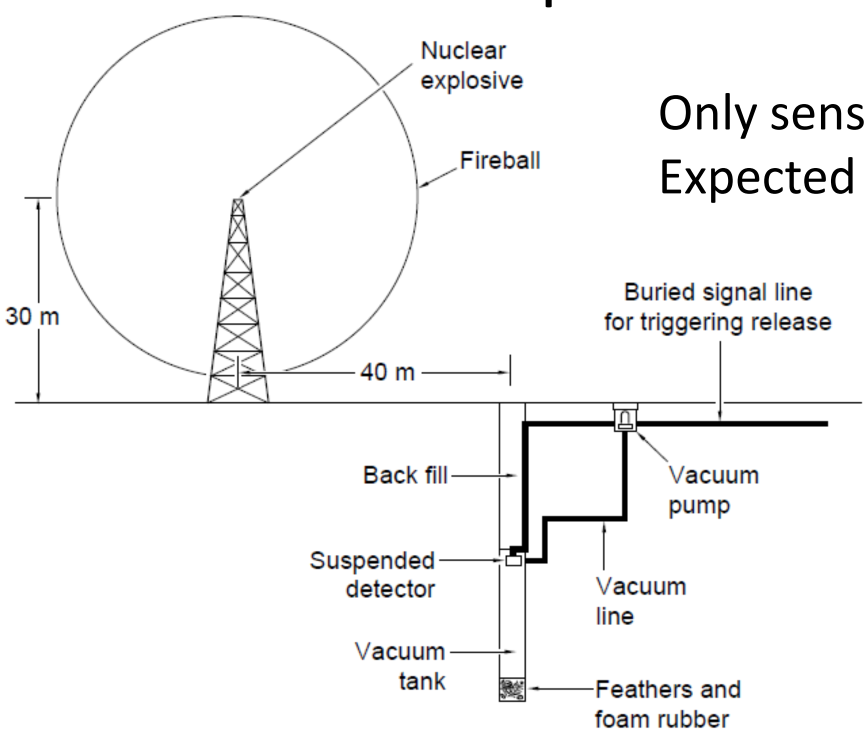
$$m_\nu < 1\ keV$$

Detecting Anti-Neutrinos

Fermi theory: $\boldsymbol{n \rightarrow p + \beta^- + \bar{\nu}}$

Inverse reaction: $\boldsymbol{\bar{\nu} + p \rightarrow n + \beta^+}$

1952 – Reines & Cowan propose to detect the β^+ annihilation in liquid scintillator



Only sensitive to cross sections $\sigma \sim 10^{-40}\ \mathrm{cm}^2$
Expected cross section is $10^{-44}\ \mathrm{cm}^2$

Sensitivity dominated by background count rate.

The same sensitivity would be achieved at a reactor.

Detecting Anti-Neutrinos

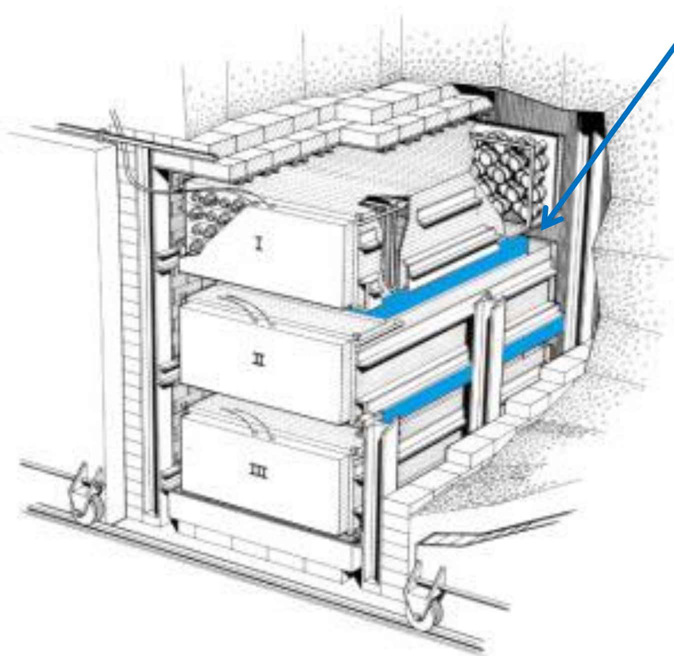
Delayed coincidence – neutron capture on cadmium…

$$\bar{\nu} + p \rightarrow n + e^{+} \qquad e^{+}e^{-} \rightarrow \gamma\gamma \quad \textbf{(1.05 MeV)}$$

$$n + {}^{108}Cd \rightarrow {}^{109}Cd^{*} \rightarrow {}^{109}Cd + \gamma \quad \textbf{(9 MeV)}$$

Detect neutron capture within 5 μs of $e^{+}e^{-}$ annihilation.

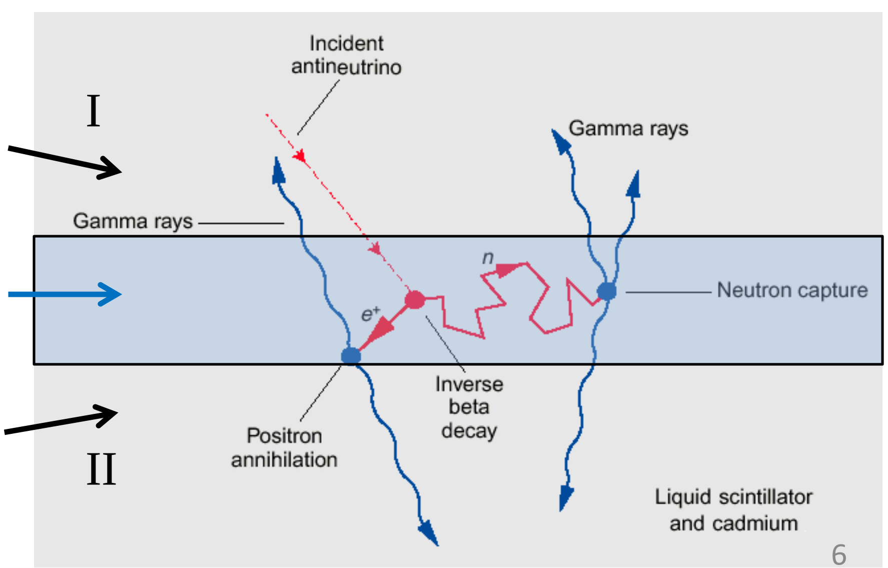
$CdCl_2$ dissolved in water



Liquid Scintillator

Water

Liquid scintillator



Detecting Neutrinos

- How do we know that ν and $\bar{\nu}$ are different?
- Pontecorvo's method:

$$\nu + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

  - Natural abundance of ${}^{37}Cl$ is 24%
  - Tetrachloroethylene (C_2Cl_4) is non-flammable, inexpensive
  - ${}^{37}Ar$ is unstable with a half-life of 35 days
  - Production and decay rates in equilibrium
  - Small numbers of ${}^{37}Ar$ atoms can be extracted from a large volume of C_2Cl_4.
- Described in a lecture to physics students at McGill and written up in NRC Report P.D.-205
  - Immediately classified by the US Atomic Energy Commission

Detecting Neutrinos

Ray Davis, 1955

55 gallons of CCl_4

A second system consisted of 1000 gallons of CCl_4

Argon Extraction

- Flush with helium
- Freeze onto charcoal trap cooled with LN_2
- Count ^{37}Ar with G-M tube
- Demonstrated greater than 90% extraction efficiency

$$\nu + {}^{37}Cl \rightarrow e^- + {}^{37}Ar$$

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

Attempt to Detect the Antineutrinos from a Nuclear Reactor by the $Cl^{37}(\bar{\nu},e^-)A^{37}$ Reaction*

RAYMOND DAVIS, JR.
Department of Chemistry, Brookhaven National Laboratory, Upton, Long Island, New York
(Received September 21, 1954)

Unlike photons and π^0 mesons, which are their own anti-particles, ***neutrinos and anti-neutrinos are different!***

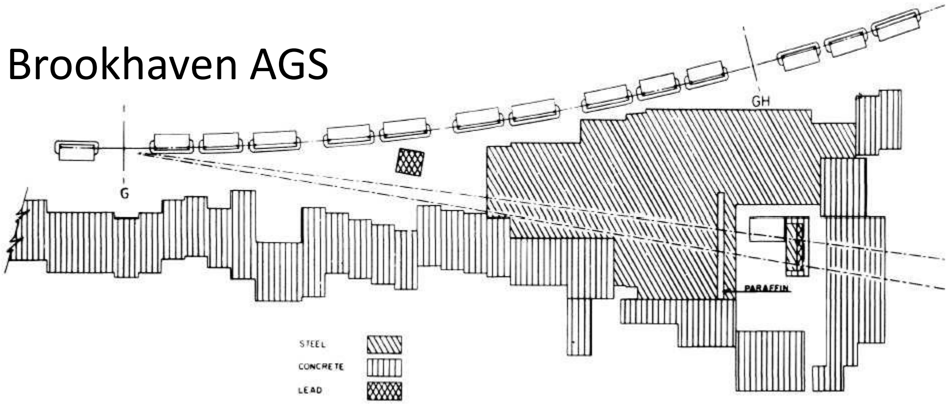
Muon Neutrinos

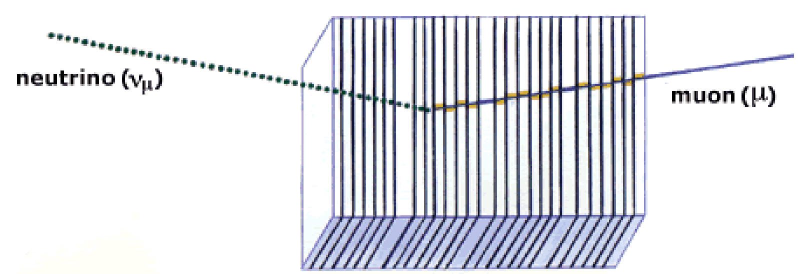
1959 – Bruno Pontecorvo considered the production of neutrinos at accelerators:

$$\pi^+ \rightarrow \mu^+ \boldsymbol{\nu_\mu} \qquad \pi^- \rightarrow \mu^- \boldsymbol{\bar{\nu}_\mu}$$

$$\boldsymbol{\nu_\mu} + n \rightarrow p + \mu^- \qquad \boldsymbol{\bar{\nu}_\mu} + p \rightarrow n + \mu^+$$

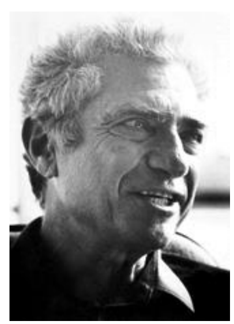
Brookhaven AGS






Leon Lederman

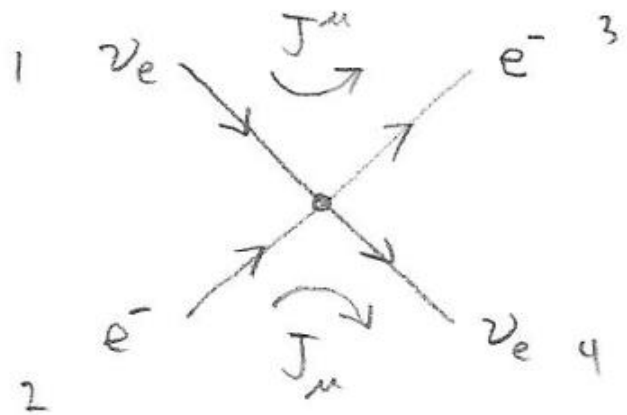

Melvin Schwartz


Jack Steinberger


1988

Elastic Neutrino Scattering

- Sufficient to use the Fermi 4-point interaction
- First, consider elastic scattering $\nu_e + e^- \to \nu_e + e^-$



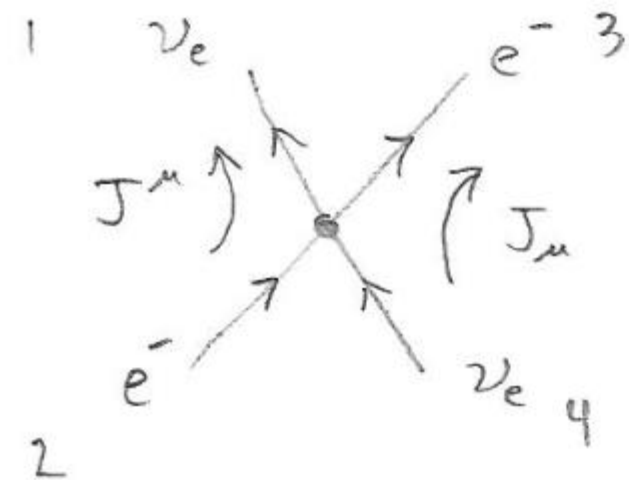
$$J^\mu = \bar{u}_2 \frac{1}{2} \gamma^\mu (1 - \gamma^5) u_1$$

$$J_\mu = \bar{u}_4 \frac{1}{2} \gamma_\mu (1 - \gamma^5) u_2$$

$$|\bar{\mathcal{M}}|^2 = 64 G_F^2 (p_1 \cdot p_2)(p_3 \cdot p_4)$$
$$= 16 G_F^2 s^2$$
$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2$$
$$\approx 2p_1 \cdot p_2 \approx 2p_3 \cdot p_4$$

Elastic Neutrino Scattering

- Next, consider elastic $\bar{\nu}_e$ scattering $\bar{\nu}_e + e^- \to \bar{\nu}_e + e^-$



This is the same diagram except with $1 \leftrightarrow 4$

$$|\overline{\mathcal{M}}|^2 = 64 G_F^2 (p_4 \cdot p_2)(p_3 \cdot p_1)$$
$$= 16 G_F^2 t^2$$
$$t = (p_1 - p_3)^2 = (p_2 - p_4)^2$$
$$\approx -2 p_1 \cdot p_3 \approx -2 p_2 \cdot p_4$$

Elastic Neutrino Scattering

- In both cases we can consider the cross section in the center-of-mass frame:

$$p_1 = \left(\frac{\sqrt{s}}{2}, 0, 0, \frac{\sqrt{s}}{2}\right)$$

$$p_3 = \left(\frac{\sqrt{s}}{2}, \frac{\sqrt{s}}{2}\sin\theta, 0, \frac{\sqrt{s}}{2}\cos\theta\right)$$

$$t = -\frac{1}{2}s(1-\cos\theta)$$

- Incident flux: $F = 2s$
- Phase space: $dQ = \frac{1}{32\pi^2}d\Omega$

$$d\sigma = \frac{|\bar{\mathcal{M}}|^2}{F}dQ$$

Elastic Neutrino Scattering

- Differential scattering cross section:

$$d\sigma = \frac{4G_F^2 s}{64\pi^2}(1-\cos\theta)^2 d\Omega$$

$$\frac{G_F^2 s}{8\pi}(1-y)^2 dy$$

$(y = \cos\theta)$

- Total cross section:

$$\sigma = \frac{G^2 s}{3\pi}$$

Elastic Neutrino Scattering

- Normally this experiment would be carried out in the lab frame with the electron initially at rest.

$$p_\nu = (E_\nu, \vec{p}_\nu),\ |\vec{p}_\nu| = E_\nu$$
$$p_e = \left(m_e, \vec{0}\right)$$
$$s = (p_\nu + p_e)^2 \approx 2E_\nu m_e$$

- Total cross section:

$$\sigma = \frac{2G_F^2 m_e E_\nu}{3\pi}$$

- If $E_\nu \sim 5\ \mathrm{MeV}$ then $\sigma = 2.9 \times 10^{-44}\ \mathrm{cm}^2$
- This small cross section is typical of neutrino interactions.

Muon Neutrino Beams

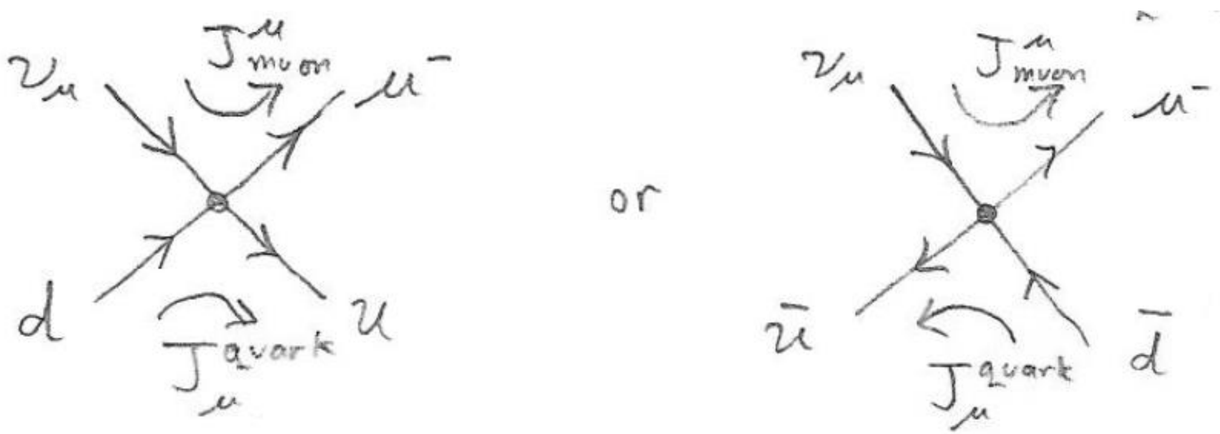
- A wide-band neutrino beam is produced by a high energy proton beam on a target
  - Lots of pions and kaons are produced
  - These decay to muons and muon neutrinos
  - Muons decay to electrons and neutrinos
- A narrow-band beam is produced from decays of pions and kaons that are selected with a specific range of momenta.
- Muon neutrino beams can interact with thick nuclear targets

$$\nu_\mu + N \rightarrow \mu^- + X$$
$$\bar{\nu}_\mu + N \rightarrow \mu^+ + X$$

- The muons will ionize the instrumented parts of the target and are easily detected.

Probing Nuclear Structure

- The muon neutrino will either interact with a d-quark or a $\bar{u}$-quark.



- These diagrams are the same as the elastic scattering diagrams except with the momenta re-labeled.

Probing Nuclear Structure

$$\frac{d\sigma}{d\Omega}\left(\nu_\mu d \to \mu^- u\right) = \frac{G_F^2 s}{4\pi^2}$$

$$\frac{d\sigma}{d\Omega}\left(\bar{\nu}_\mu u \to \mu^+ d\right) = \frac{G_F^2 s}{16\pi^2}(1 + \cos\theta^*)^2$$

$$\frac{d\sigma}{d\Omega}\left(\nu_\mu \bar{u} \to \mu^- \bar{d}\right) = \frac{G_F^2 s}{16\pi^2}(1 + \cos\theta^*)^2$$

$$\frac{d\sigma}{d\Omega}\left(\bar{\nu}_\mu \bar{d} \to \mu^+ \bar{u}\right) = \frac{G_F^2 s}{4\pi^2}$$

- To calculate cross sections in the lab frame, express these in terms of $y = (E_\mu - E_\nu)/E_\nu$

$$1 - y = \frac{1}{2}(1 + \cos\theta^*)$$

- But what is s when we are colliding with quarks inside a nucleus?

Parton Density Functions

- Suppose that a quark carries a fraction, x, of the total momentum of the nucleus

$$p_\nu = \left(\frac{\sqrt{s}}{2}, 0, 0, \frac{\sqrt{s}}{2}\right)$$

$$p_q = \left(\frac{x\sqrt{s}}{2}, 0, 0, -\frac{x\sqrt{s}}{2}\right)$$

$$\hat{s} = \left(p_\nu + p_q\right)^2 = xs$$

- The differential cross sections can be expressed

$$\frac{d\sigma}{dxdy}\left(\nu_\mu N \rightarrow \mu X\right) = \sum_i f_i(x)\left(\frac{d\hat{\sigma}_i}{dy}\right)$$

- $f_i(x)dx$ is the probability for finding a quark of type i with momentum fraction between x and $x + dx$.

Probing Nuclear Structure

- We can't *a priori* calculate these probability densities
- Isospin symmetry:

$$d_n(x) = u_p(x)$$
$$\bar{u}_n(x) = \bar{d}_p(x)$$

- For an isoscalar target like liquid deuterium, we will average over protons and neutrons:

$$\frac{d\sigma}{dxdy}(\nu N) = \frac{G_F^2 xs}{2\pi}\left[u(x) + d(x) + \left(\bar{u}(x) + \bar{d}(x)\right)(1-y)^2\right]$$
$$\frac{d\sigma}{dxdy}(\bar{\nu} N) = \frac{G_F^2 xs}{2\pi}\left[\bar{u}(x) + \bar{d}(x) + \left(u(x) + d(x)\right)(1-y)^2\right]$$

Probing Nuclear Structure

- In the lab frame,

$$s = (p_\nu + p_N)^2 = 2M_N E_\nu$$

- These cross sections can be made relatively large using very high-energy neutrino beams.
- Integrate over the parton densities to define:

$$Q \equiv \int_0^1 x\big(u(x) + d(x)\big)dx$$

$$\bar{Q} = \int_0^1 x\left(\bar{u}(x) + \bar{d}(x)\right)dx$$

- And recall that

$$\int_0^1 (1-y)^2 dy = \frac{1}{3}$$

Probing Nuclear Structure

$$\sigma(\nu N) = \frac{G_F^2 M_N E_\nu}{\pi}\left(Q + \frac{1}{3}\bar{Q}\right)$$

$$\sigma(\bar{\nu} N) = \frac{G_F^2 M_N E_\nu}{\pi}\left(\bar{Q} + \frac{1}{3}Q\right)$$

- If we were to measure σ/E_ν as a function of E_ν, we would expect it to remain constant.
- Furthermore, we expect that

$$R = \frac{\sigma(\bar{\nu} N)}{\sigma(\nu N)} = \frac{1 + 3\bar{Q}/Q}{3 + \bar{Q}/Q}$$

Probing Nuclear Structure

- If there were no anti-quarks in the nucleon, then we would expect that $R = 1/3$.
- The cross sections are indeed found to be directly proportional to the beam energy but the observed ratio is

$$R \sim 0.45 \Rightarrow \bar{Q}/Q \sim 0.14$$

- This provides direct evidence that neutrinos can interact with the anti-quarks from the sea of virtual $\bar{q}q$ pairs within the nucleon.

Probing Nuclear Structure

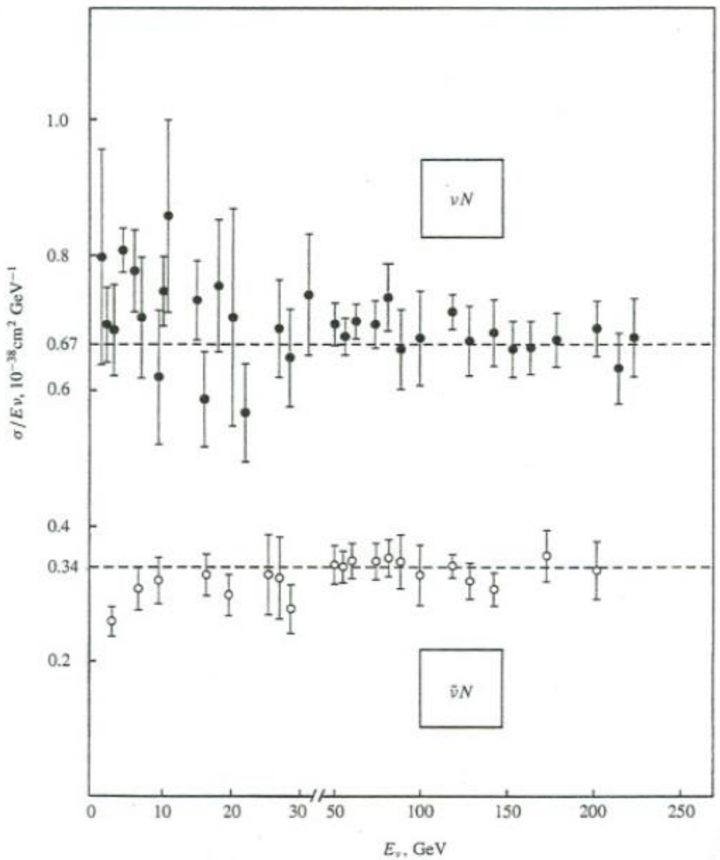


Fig. 5.13. Neutrino and antineutrino cross-sections on nucleons. The ratio σ/E_ν is plotted as a function of energy and is indeed a constant, as predicted in (5.45) and (5.46).