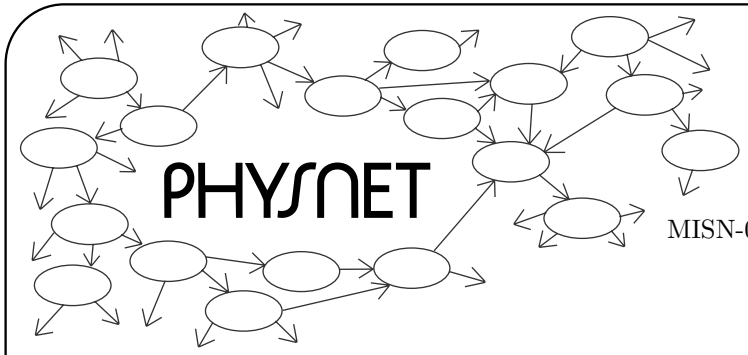
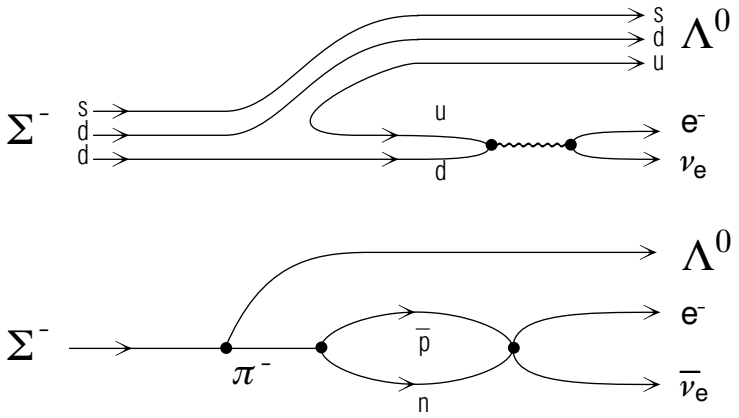


MISN-0-281

THE WEAK INTERACTION



Project PHYSNET Physics Bldg. Michigan State University East Lansing, MI

THE WEAK INTERACTION

by

J. Christman

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Title: **The Weak Interaction**

Author: J. R. Christman, Dept. of Physical Science, U.S. Coast Guard Academy, New London, CT

Version: 11/8/2001 Evaluation: Stage B1

Length: 2 hr; 16 pages

Input Skills:

1. Interpret Particle Diagrams and give the associated coupling constants (MISN-0-279).

Output Skills (Knowledge):

K1. List the three categories of weak interactions and give examples and possible Particle Diagrams for each.

K2. Give arguments that lead to predictions of the mass and spin of the W particles.

Output Skills (Problem Solving):

S1. Given a weak decay, devise a plausible Particle Diagram for it, showing the weak interaction as a four-fermion interaction.

S2. Given a weak decay, devise a plausible Particle Diagram for it, showing the weak interaction as the exchange of a (charged) W or a (neutral) Z^0.

External Resources (Required):

1. M. J. Longo, *Fundamentals of Elementary Particle Physics*, Prentice-Hall (1973).
2. *Scientific American*, March, 1959.

Post-Options:

1. "SU(3) and the Quark Model" (MISN-0-282).
2. "Current Work in Elementary Particles" (MISN-0-284).

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THE WEAK INTERACTION

by

J. Christman

1. Overview

This module fills in some details of the weak interaction. In particular, it deals with the basic couplings of the interaction and with the W particles which are exchanged in it.

2. Assigned Readings

- Chapter 6, Longo
- S. B.,Treiman, "The Weak Interactions," *Scientific American*, March, 1959.

3. Characteristics of the Weak Interaction

3a. The Weak Force: Universal. All particles participate in the weak interaction in the sense that all known particles (except the resonances) have been observed to participate in an interaction or decay that involves the weak force (at one or more vertices in the associated Particle Diagram). Study of the weak force, however, is complicated by the strong interaction: some interactions may proceed in more than one step, the first step being a strong decay to other particles, some of which then interact weakly. The strong process takes place in such a short time and over such a small distance that it is impossible to observe and hence it is impossible (except by indirect evidence) to ascertain whether or not the strong interaction actually took place. This makes deduction of the weak part of the interaction uncertain.

3b. Huge Fluxes For Direct Neutrino Observation. Neutrinos are the only particles that interact via the weak force alone so they make ideal "bullets" to study the weak interaction. The weak interaction is so weak, however, that only about 1 neutrino in every 10^{12} undergoes an interaction with the nucleons in fluids used to detect neutrinos. So the experimental study of the weak interaction requires enormous neutrino fluxes and also detection chambers the size of large rooms.

The participation of a neutrino guarantees that the interaction is weak. However, it is extremely difficult, in most cases, to show that a neutrino is, in fact, even present.

3c. Change in S if One Weak Vertex. All first order weak interactions (i.e., decays with one weak vertex), either do not change strangeness or else change strangeness by ± 1. That is, $\Delta S = 0, \pm 1$ for first order weak decays. Second order weak interactions, decays with two weak vertices, are extremely rare and will not be considered here.

3d. Range of the Weak Interaction. Theories suggest that the range of the weak interaction is on the order of $10^{-16} - 10^{-17}$ m, which is shorter than the range of the strong interaction.

3e. A Four-Fermion Interaction. A weak interaction vertex in a Particle Diagram must have exactly four particle lines and the particles must all be fermions. The interaction strength at the vertex is denoted g_w.

4. Categories of Weak Interaction

4a. Categories Based on Particles Involved. Weak interactions are classified in three categories: "leptonic," in which only leptons are involved; "semi-leptonic," in which both leptons and hadrons are involved; and "hadronic," in which only hadrons are involved.

4b. Examples of Weak "Leptonic" Processes. Here are two scattering reactions and a decay involving only leptons in the initial and final states (note that the neutrino is chargeless so the scattering cannot be electromagnetic):

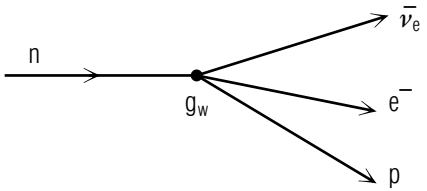
$$\nu_e + e^- \rightarrow \nu_e + e^- \qquad \text{(scattering)}$$

$$\nu_\mu + \mu^- \rightarrow \nu_\mu + \mu^- \qquad \text{(scattering)}$$

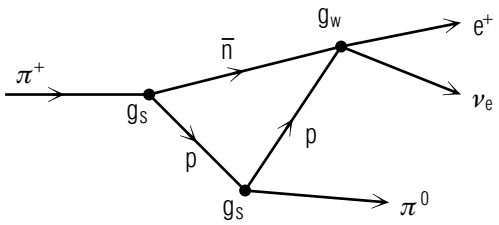
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

4c. Examples of Weak "Semi-Leptonic" Processes. Here are some diagrams for Weak "Semi-Leptonic" Processes:

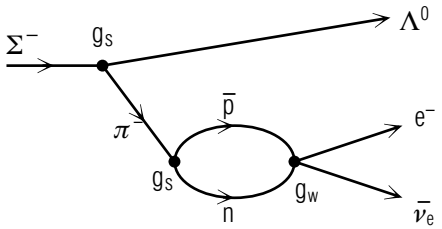
$n \rightarrow p + e^- + \bar{\nu}_e$ (nuclear β decay):



$\pi^+ \rightarrow \pi^0 + e^+ + \nu_e$:

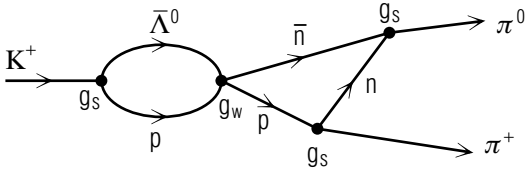


$\Sigma^- \rightarrow \Lambda^0 + e^- + \bar{\nu}_e$:

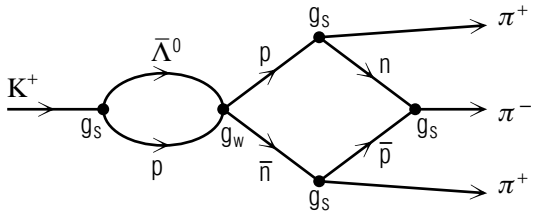


4d. Examples of Weak "Hadronic" Processes. Here are some diagrams for Weak "Hadronic" Processes:

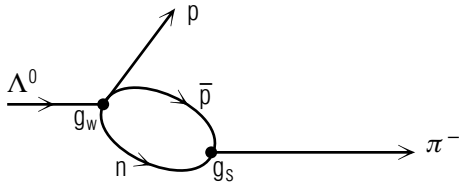
$K^+ \rightarrow \pi^+ + \pi^0$:



$K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$:



$\Lambda^0 \rightarrow p + \pi^-$:



4e. Strong Decays Occur Before Weak Decays. The hadrons that enter the weak vertex of the above diagrams are the lowest mass baryons with $S = 0$ and $S = 1$. All hadrons couple strongly to at least one of these baryons, and since the strong interaction is so fast one expects an initial hadron to first interact strongly until one of these low mass baryons is produced.

5. The Intermediate Vector Boson

5a. The W Particle as the Weak-Force Meson. The electromagnetic interaction is carried by the photon and the strong interaction is carried by hadrons, in the sense that the interactions are "caused by" exchange of such intermediary particles. Similarly, the weak interaction is carried by the "intermediate vector boson" and its symbol is W. There is a positively charged W^+, a negatively charged W^-, and a neutral W^0. These particles can be produced by appropriate pairs of weakly interacting particles and they decay into appropriate pairs:

$$p + \bar{n} \leftrightarrow W^+ \qquad \bar{p} + n \leftrightarrow W^-$$
$$p + \bar{\Lambda}^0 \leftrightarrow W^+ \qquad \bar{p} + \Lambda^0 \leftrightarrow W^-$$
$$\mu^+ + \nu_\mu \leftrightarrow W^+ \qquad \mu^- + \bar{\nu}_\mu \leftrightarrow W^-$$

For example, β decay proceeds according to:

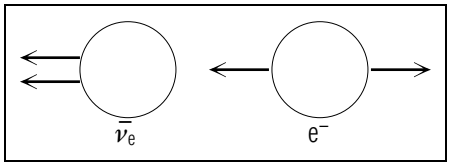
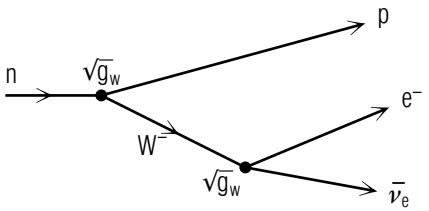


Figure 1. Spins and momenta from W^- decay.



The coupling constant at each vertex is $\sqrt{g_w}$ to make the overall coupling constant g_w.

5b. The Mass of the W Particle. Since the range of the weak interaction is less than 10^{-16} m, the mass of the W must be greater than an amount determined by the "uncertainty principle":

$$mc^2 > \frac{\hbar}{\Delta t} = \frac{\hbar c}{R} = \frac{(1.05 \times 10^{-}34) \times (3 \times 10^8)}{10^{-16}} = 3.15{\times}10^{-10}\,\mathrm{J} = 2.0\,\mathrm{GeV}\,.$$

(Note: $1\,\mathrm{GeV} = 10^3\,\mathrm{MeV}$.) Experimentally, W particles have been seen. The observed mass of the W is approximately 80 GeV.

5c. The Spin of the W Particle. The spin of the W can be deduced from observations of the spins of its decay products. Consider, for example, the β decay of the neutron (see the diagram in Sect. 5a and Fig. 1, this section). In the center of mass frame of the electron and antineutrino, the spin of the antineutrino is $\hbar/2$ in the direction of its momentum (this is true for the antineutrino in any frame) and the spin of the electron is observed to be $\hbar/2$ in the direction opposite to its momentum. The orbital angular momentum is zero. If the particles result from the decay of a W, the spins and momenta of the decay products look as in Fig. 1. Note that the total spin is $\hbar$, to the left. Since angular momentum is conserved, the spin of the W^- must have been $\hbar$. This is in fact the reason for its name "intermediate vector boson." An integer spin particle is a boson and a spin 1 particle has associated with it a vector field (another vector boson, the photon, is associated with the vector electromagnetic field). It is also easy to deduce that the W particles have electron family number 0, muon

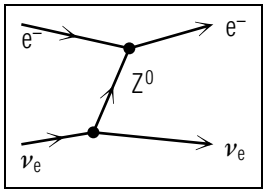


Figure 2. The weak-interaction exchange of a neutral particle (the Z).

family number 0, and the baryon family number 0.

5d. The Neutral Weak Boson. A neutral boson is not needed for exchange in the usual weak couplings of nuclear physics; all of them involve a transfer of charge and so involve the exchange of charged W's. However, the observed weak scattering of one lepton by another does require the exchange of a neutral boson (see Fig. 2.). Our current theoretical understanding is that the W^0 cannot itself be observed, but that it and another unobservable particle combine two different ways to form the observed weak-interaction Z^0 and the well-observed electromagnetic-interaction γ (the "photon"). Apart from lepton scattering, other reactions such as

$$\nu_\mu + \mathrm{p} \rightarrow \nu_\mu + \mathrm{p} + \pi^0$$

can occur via the exchange of the Z^0.

5e. A Problem with Neutral K Decay. An important example of weak neutral exchange should be the decay of the neutral kaon. The more usual decay products include at least one pion. The decay to leptons,

$$\mathrm{K}^0 \rightarrow \mu^+ + \mu^-\,,$$

is extremely rare. With a Z^0 existing, K^0 can decay that way via a first order weak decay and for some time the rarity of that decay mode was taken as evidence that the neutral "weakon" did not exist. With evidence for the Z^0 in neutrino scattering (see Sect. 5d), a new explanation was required for the rarity of the neutral kaon decay to muons. The solution is another quantum number, called "charm," which we shall discuss elsewhere.[1]

Acknowledgments

Preparation of this module was supported by the United States Coast Guard Academy for a Directed Studies Program. Preparation of this

[1] See "Color and Charm" (MISN-0-283).

module was supported in part by the National Science Foundation, Division of Science Education Development and Research, through Grant #SED 74-20088 to Michigan State University.

PROBLEM SUPPLEMENT

Note: If you do not understand how an answer in this supplement was arrived at, kindly go back to the text and work through it carefully. Make sure you understand all of the text examples before coming back to this supplement. The text is organized for learning, whereas this supplement is designed to help you *test* whether you learned the subject from the text.

Problems:

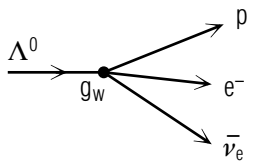
Devise plausible diagrams for the following weak decays, both without and with intermediate "weakons."

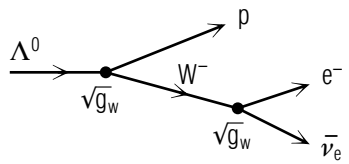
1. $\Xi^0 \rightarrow \Lambda^0 + \pi^0$ (C)
2. $K^+ \rightarrow \pi^0 + e^+ + \nu_e$ (B)
3. $\pi^+ \rightarrow \mu^+ + \nu_\mu$ (E)
4. $\Lambda^0 \rightarrow p + e^- + \bar{\nu}_e$ (A)
5. $\Sigma^- \rightarrow \Lambda^0 + e^- + \bar{\nu}_e$ (D)

Note: In some cases there are a number of legitimate possibilities for intermediate states. For example, in Answer (C) the (p, $\overline{p}$) intermediate state could equally well be (n, $\overline{n}$).

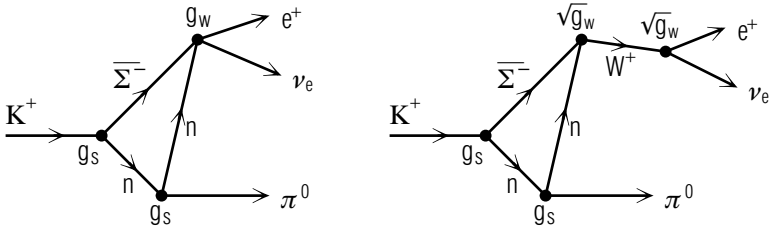
Answers:

(A)





(B)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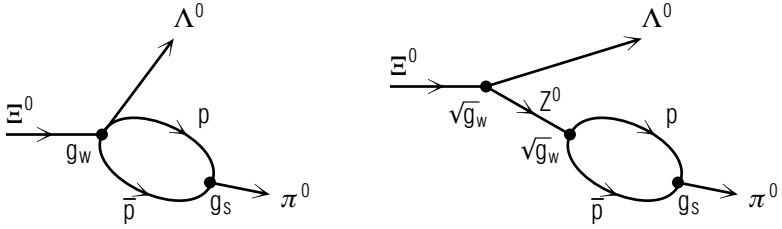
(C)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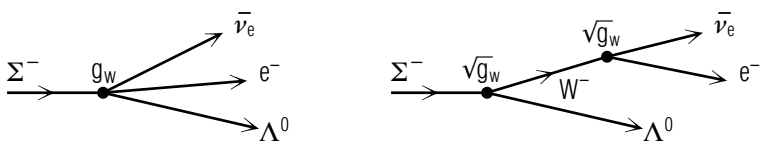
(D)


$\overline{\nu}_e$
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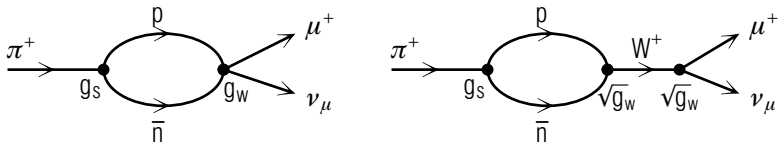
W^-
Λ^0

(E)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