Lecture Notes on
WEAK INTERACTIONS
and Topics in Dispersion Physics from the Second Bergen International School of Physics—1962

CHRISTIAN FRONSDAL, EDITOR

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and Topics in Dispersion Physics

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Preface

This volume contains most of the lectures given at the 2nd annual Bergen International School of Physics, which was in session from May 28 to June 13, 1962. The theme of the session was "Weak Interactions," with emphasis on the application of dispersion theoretic methods.

Because, inevitably, new experimental results have been obtained in the nearly 6 months that have passed between the time these lectures were presented and the appearance of this book, I shall attempt to review the most important recent developments. I shall follow the systematic exposition of Professor Treiman's lectures rather closely, referring the reader to details given in other lectures whenever appropriate.

The most fascinating news items announced by the "weak" physicists in recent years have concerned the number of neutrinos that one has to contend with. Professor Bernardini's lectures contain a historical introduction, beginning with Fermi's brilliant neutrino hypothesis. Until 1957, the number of neutrino states for a given momentum was believed to be four. Then the discovery of parity nonconservation revealed that neutrinos are always polarized in production, so that two states might suffice; this was certainly the prevailing view for the next few years. There was always the difficulty of the so-called forbidden processes, discussed in detail by Professor Di Lella; as these turned out to be quite obstinate difficulties, these was a growing feeling among physicists that perhaps four neutrinos were needed after all. When these lectures were given, the answer was still in doubt, but not for long. At the 1962 High-Energy Conference in Geneva, the Brookhaven spark-chamber group announced the results of the neutrino-absorption experiment discussed by Professor Treiman (p. 97). [See The Physical Review Letters, 9, 36, (1962).] There are now four neutrino states, two of them coupled to the electron and the other two coupled to the muon.

Some of the asymmetry parameters in hyperon non-leptonic decay have been remeasured. (See the report of F. S. Crawford in the Proceedings of the 1962 High Energy Conference at CERN, p. 827.) New measurement on K_{e3} decay have recently been reported by Brown, Kadyk, Trilling, Van de Walle, Roe, and Sinclair at Berkeley. (Preprint August 1962.)

The lectures by Professors Primakoff, Fujii, and Predazzi on weak form factors assume a knowledge of dispersion theoretic methods. At the present time, all efforts to relate to experiment have been based on the assumption that strong-interaction effects can be represented by poles in the form factors; Professor Fubini's lectures introduce the uninitiated to the craft of polology.

The concluding sets of lectures are more in the nature of research reports.

In addition, the participants in the school were treated to a beautiful set of lectures by Professor Mandelstam. As these followed closely his subsequently published article in Reports on Progress in Physics, a reproduction of this paper is included at the end of the volume. For their gracious permission to reprint it here, I am indebted to The Physical Society, London.

The 1962 session of the Bergen International School of Physics was made possible through a grant from the NATO Science Council. I am happy to take this occasion to express the gratitude of all concerned.

CHRISTIAN FRONSDAL

Los Angeles, California
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Contents

Acknowledgment

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Introduction to Beta Decay

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I. GENERAL CONSIDERATIONS

Our present understanding of weak interactions is almost exclusively based on low-momentum transfer, strangeness conserving transitions, such as the two fundamental processes of beta-decay (involves momentum transfers of about 1 MeV) and muon-decay (about 100 MeV). To the other already discovered and partially analyzed weak processes (strange particles with leptonic and non-leptonic decays), we cannot attach the verb "to understand" with a comparable level of confidence. This is the domain where the classic Fermi theory in its modern V-A version, due to Feynman - Gell-Mann and Marshak-Sudarshan, has been shown to be particularly successful. I shall limit my lectures to discussing some more or less recent experiments, the results of which are giving supplementary support to the already rather well established V-A theory.

As I am lecturing at the beginning of this course, I shall make a brief introduction to recall to your memory some essential points of the V-A theory. I am not very profoundly versed in it. However, I may simply say that since the discovery of the parity violation I was strongly attracted by the clear intellectual value of this never-old field of physics, and now I take this pleasant occasion to convey to you the great interest I feel for it.

Some of the experiments whose significance I should like to discuss may be called the "key experiments" on "typical weak interactions". In this category are neutron beta decay

$$n \rightarrow p + e^- + \nu \,, \tag{1}$$

and the inverse process of electron capture

$$p + e^- \rightarrow n + \nu \,. \tag{1'}$$

The fact that process (1) has an antineutrino rather than a neutrino in the final state is a matter of definition. Reaction (1), written in the form (1'), may be visualized as a collision (scattering) process; that is, as a collision where the colliding neutron-neutrino pair is converted into a proton-electron pair, similarly to the way an electron-proton pair is scattered into another one via electromagnetic forces.

As long ago as in 1934 Fermi constructed his celebrated theory on the model of electro-dynamics. Today this theory holds almost intact in ts essentials, and it may be useful for a better evaluation of the meaning and importance of the experiments we shall discuss, to say a few introductory words about it. There are several versions of the history of this great achievement in science from which the modern field theory started, but all of them begin with the typical deep and simple way of thinking which was a unique characteristic of Fermi's intellect. In its modern version the classic electromagnetic interaction is

$$eA_\mu(\bar{\psi}\gamma_\mu\psi) \,. \tag{2}$$

Dealing with the reactions (1) and (1') Fermi assumed that the nucleon generate electron-neutrino radiation in proportion to the "weak current"

$$j_N = \bar{\psi}\tau_+\gamma_\mu\psi = \bar{\psi}_p\gamma_\mu\psi_n \,.$$

However, there is an essential difference between the emission (asorption) of a photon by a charge-current and the emission of the e-ν radiation by a nucleon weak current. In the first case, one boson is emitted during a one-to-one fermion transition; in the second, a pair of fermions is coupled with another pair. We are well acquainted with the idea that the proton and the neutron are two states of the same particle; the nucleon N, and this extrapolation from the concept of an electrical current to a weak current seems quite natural.

In terms of Feynman graphs, the electromagnetic and beta-decay interactions may be represented as in Fig. 1. These diagrams

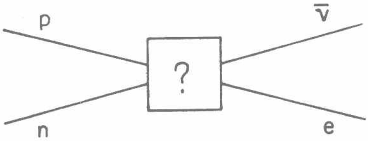

Figure 1.

exemplify a general rule which stems from angular momentum conservation. Fermions are always created and destroyed in pairs, bosons can be absorbed or emitted singly. Actually if one wants to push the electrodynamic analogy, one would do better to compare reaction (1') with, for instance, the nucleon-electron scattering (Fig. 2a), whose dominant term is Møller scattering, shown in Fig. 2b.

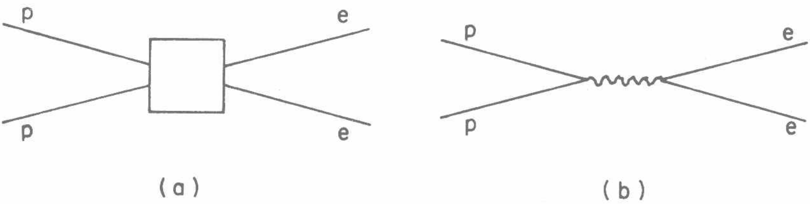

Figure 2.

In other words; the analogy brings us to consider beta-decay as a current-current interaction

$$\int j_N \cdot j_e d\tau \tag{3}$$

such as the classic Ampere theory of electromagnetism. Here the current may be considered to be the two Dirac charge-changing currents nucleon current : $\bar{\psi}_p \gamma_\mu \psi_n$,

lepton current : $\bar{\psi}_e \gamma_\mu \psi_\nu$.

An interaction which determines the reaction (1') could then be written

$$H_I = G(\bar{\psi}_p \gamma_\mu \psi_n)(\bar{\psi}_e \gamma_\mu \psi_\nu) \; . \tag{3'}$$

However, between interactions (3) and (3') there is now a new essential difference: (3') is a local; that is, a point-like interaction, while (3) is not. The interaction between the current j_N and j_e occurs via intermediate photons. Furthermore, the interaction (3') contains implicitly the far from trivial idea of the conversion of a neutrino into an electron being associated with the change of the nucleon from the neutron to the proton state. In a mysterious way the electric charge transits from the nucleon to the neutrino, converting it into an electron. To conclude here the analogies with electro-dynamics, one could visualize reaction (1') as proceeding like electron-proton scattering, specializing the block diagram of Fig. 1 to the form of Fig. 3. Here the arrow represents a virtual charged vector boson W,

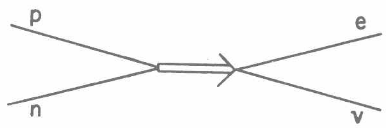

Figure 3.

supposed mediator of the weak interactions. At this point the analogy with the photon case is strong and very tempting, but when one attempts to push it as far as is already required by known fact, one meets several very serious difficulties. However, if there exist two neutrinos (as was suggested by Pontecorvo, and as now appears probable), the chances that the intermediate heavy boson W does indeed exist is not safely ignored. With the low limits now established for the neutrinoless decay of a muon into an electron and a photon, and rumors concerning the Brookhaven experiment, the possibility of two neutrinos now becomes a more and more attractive and fashionable idea.

The operator (3') is actually what has been called, since a long time, the pure Fermi interaction; H_I is the scalar product of two four-vectors.

II. LEPTON CONSERVATION

The principle of lepton conservation was stated by Konopinsky et al[1] in 1953 in connection with double beta-decay. A lepton number of either +1 or -1 is assigned to all leptons (neutrinos, electrons and muons); a particle and its antiparticle have opposite lepton numbers. The lepton numbers of baryons and mesons are taken to be zero. The principle of lepton conservation states that, in any given process the total number of leptons (i. e. number of leptons minus number or antileptons) is conserved.

Due to the above-mentioned fact that fermions are always created or destroyed in pairs, this is equivalent to saying that such pairs are always made up of a lepton and an antilepton. For instance, the fundamental reaction

$$\mu^{\pm} \rightarrow e^{\pm} + \text{(two neutrinos)}$$

has to be written

$$\mu^{\pm} \rightarrow e^{\pm} + \nu + \bar{\nu} \,. \qquad (4)$$

This is more than a mere convention. There is an experiment, first discussed by Furry[2], which would be possible only if the neutrino is its own antiparticle.

This is the double beta-decay

$$Z \rightarrow (Z+2) + 2e^{-} \,. \qquad (5)$$

Here a nucleus first emits an electron by neutron decay, while the accompanying antineutrino is reabsorbed by

$$\bar{\nu} + n \rightarrow p + e^- . \qquad (6)$$

If this were possible, then a neutrino could be emitted in the beta-decay of the neutron, which would make the neutrino and the antineutrino experimentally indistinguishable.

This process would, for instance, be energetically possible for

$$Te^{130} \rightarrow X^{130} + 2e^- . \qquad (7)$$

It would be expected to occur with an observable lifetime of 6×10^{14} years if the virtual reabsorbtion were fully allowed. Inghram et al[3] have found that the lifetime is more than 1.4×10^{21} years.

The celebrated experiment of Reines and Cowan[4], where the pile neutrinos (coming mainly from neutron decays) are absorbed, goes according to the reaction

$$(\text{pile neutrinos}) + p \rightarrow n + e^+ , \qquad (8)$$

with a cross-section which agrees to within 20 percent with the expected allowed value. Davis[5] has observed the reaction

$$(\text{pile neutrinos}) + C^{37}_{17} \rightarrow A^{37}_{18} + e^- .$$

The conclusion is that lepton conservation is (or will be, whenever well-established experimentally) 'a physical law in its own right and not directly connected with the number of states available to the neutrino'.

III. SOME CONSEQUENCES OF LEPTON CONSERVATION

If one considers the negative electron as a particle with leptonic number +1, on the basis of lepton conservation the μ^- also has lepton number +1. Thus consistently we will call the negative (positive) electrons and muons particles (antiparticles).

Some consequences concerning allowed and forbidden transitions may immediately be derived from lepton conservation. For example, the following processes are allowed (the letter ℓ stands for an electron or a muon):

$$\pi^- \to \ell^- + \bar{\nu} \;, \qquad \pi^+ \to \ell^+ + \nu \;,$$
$$K^- \to \ell^- + \bar{\nu} \;, \qquad K^+ \to \ell^+ + \nu \;,$$
$$K_2^0 \to \pi^+ + \ell^- + \bar{\nu} \;,$$
$$\to \pi^- + \ell^+ + \nu \;.$$

On the other hand, lepton conservation forbids such processes as

$$\nu + p \to n + e^+ \;,$$
$$\mu \to e + 2\nu \;,$$
$$\to e + 2\bar{\nu} \;.$$

Finally there are processes that are allowed but not seen, for example

$$\mu \to e + \gamma \;, \qquad (8)$$
$$\to e + e + e \;, \qquad (9)$$
$$\mu + p \to e + p \;. \qquad (10)$$

These are discussed in detail in the lecture by Dr. DiLella.

IV. FERMI AND GAMOW-TELLER TRANSITIONS

The growth of known facts on beta-decays gradually make clear that the Fermi current-current interaction is unable to explain all possible types of decays and some observed angular correlations. The Fermi interaction has symmetries which impose very definite selection rules. The bulk of progress in the knowledge of nuclear quantum numbers has made it clear that some beta transitions occur at rates comparable with the most allowed ones, in spite of the fact that according to Fermi selection rules they would be strictly forbidden.

Because the nucleon recoil in beta-decay is small, one may speak in terms which are actually correct only in the non-relativistic limit. In this approximation a fermion pair is either in a singlet or in a triplet state, according to whether the spins of the leptons are parallel or antiparallel. If the electron-neutrino pair is emitted in a singlet state, the angular momentum carried away by it is equal to the orbital angular momentum L. For the so-called allowed transitions (L = 0), there is no change in spin or parity of the nucleus. In the triplet case an allowed transition is characterized by

$$|\Delta \vec{J}| = 1, \quad \Delta J = \pm 1 \text{ or } 0.$$

(but $J_i = J_f = 0$ is excluded). The triplet emission is called a Gamow-Teller transition. One often calls the 0-to-0 transition pure Fermi, and the case $J_f - J_i = \pm 1$ pure Gamow-Teller. Many observed nuclear beta-decays indicated that G. T. transitions were also possible. A classic example is the decay of He^6 to Li^6. Here $J_i = 0$ and $J_f = 1$, so it cannot be a Fermi transition. The important decay of O^{14} to N^{14}, on the other hand, is mainly a 0^+ to 0^+ transition; that is, a pure Fermi.

Referring to the fundamental reaction (1), it is clear that both types of transitions could be possible, and actually are. The pure Fermi transition rotates the isospin of the nucleon, leaving the spin unchanged; the G. T. transition flips both the spin and the isospin of the nucleon. The occurence of both F and GT transitions indicates the need for a generalization of the operator mixing the field operators of (3'). It also introduces a second interaction constant G_{GT}. With an F transition, reaction (1) ends in a proton oriented as the initial neutron. In the GT radiation, the total lepton spin has three states. Hence, for any given initial neutron state the F transition has only one channel; the GT has three.

The interactions that will be considered do not contain derivatives. According to known experimental facts (so far limited to small