Theoretical Survey of High-Energy Neutrino Interactions.

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1. – Review of weak interactions.

1·1. *General discussions.* – It may be useful to begin our discussions by reviewing briefly the present status of weak interactions.

All the known weak reactions can be classified phenomenologically into one of the two main categories: leptonic or nonleptonic, depending on whether or not the leptons are present in the reaction.

All the known results on weak interactions are *compatible* with the following theoretical descriptions:

i) Time-reversal invariance (hence, *CP* invariance) (*).

ii) Two-component neutrino theory, *i.e.*

$$(1 - \gamma_5)\psi_{\nu_l} = 0 \,. \tag{1}$$

(Throughout these discussions, l stands for either μ or e.) Therefore, the spin of either ν_μ or ν_e is antiparallel to its momentum.

iii) Conservation of leptonic numbers L_e and L_μ.
Assign to each particle two numbers L_e and L_μ as follows:

	e^-	e^+	μ^-	μ^+	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	Others
L_e	1	−1	0	0	1	−1	0	0	0
L_μ	0	0	1	−1	0	0	1	−1	0

(*) *Note added in proof.* – Recently, J. H. CHRISTENSON, J. W. CRONIN, V. L. FITCH and R. TURLAY: [*Phys. Rev. Lett.*, **13**, 138 (1964)] discovered the 2π decay mode of K_2^0 which established that *CP* is, in fact, not conserved in this weak decay. The observed *CP* noninvariant amplitude is quite small, only $\sim 2 \cdot 10^{-3}$ times the *CP* invariant amplitude.

The conservation law states that, in all reactions, the algebraic sum of L_e and that of L_μ are separately conserved. Clearly, any linear combination of L_e and L_μ is also conserved.

iv) Except for the mass difference between μ and e, there is an exact symmetry with respect to the exchange $\mu \to e$ and $\nu_\mu \to \nu_e$.

The best evidence for i) is from β decay.

The evidence for ii) and the conservation of

$$L \equiv L_e + L_\mu$$

range over almost all known leptonic weak reactions.

The evidence for the separate conservation laws for L_e and L_μ comes from $K^+ \not\leftrightarrow \mu^+ + \nu_e$ and $\mu^\pm \not\leftrightarrow e^\pm + \gamma$.

The most impressive evidence for iv) is the $(g-2)$ experiment and the $\pi_{\mu 2}/\pi_{e2}$ branching ratio.

The combined effect of ii) and iii) is

$$m_{\nu_l} = 0 \,. \tag{2}$$

1·2. *Effective Lagrangian for the leptonic reactions.* – To study the high-energy neutrino reactions we need only to consider the leptonic part of the weak interaction. The presently-known leptonic reactions are adequately described by the Fermi theory in which the effective Lagrangian density is given by

$$L_{\text{eff}} = \frac{G}{\sqrt{2}} \{[j_\lambda(x)]_e \, [j^*_\lambda(x)]_\mu + \sum_{l=e,\mu} [J_\lambda(x) + \mathscr{S}_\lambda(x)][j^*_\lambda(x)]_l\} + \text{h.c.} \,, \tag{3}$$

where

$$[j_\lambda(x)]_l = i\psi^\dagger_l \gamma_4 \gamma_\lambda (1+\gamma_5)\psi_{\nu_l} \,, \tag{4}$$

$$[j^*_\lambda(x)]_l = i\psi^\dagger_{\nu_l} \gamma_4 \gamma_\lambda (1+\gamma_5)\psi_l \,, \tag{5}$$

and G is the Fermi coupling constant given by (in units $\hbar = c = 1$)

$$G \simeq 10^{-5} \, m_{\mathscr{N}}^{-2} \,, \tag{6}$$

where $m_{\mathscr{N}}$ = nucleon mass.

The three terms on the right-hand side of eq. (3) describe, respectively, the three different types of leptonic reactions: those involving only leptons such as μ decay, those involving also nonleptons but conserving strangeness such as β decay, and those involving nonleptons but not conserving strangeness