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WEAK INTERACTIONS AT ISABELLE

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S. M. Berman

Fermi envisioned his theory of weak interactions to apply to β -decay where the energies released were of order kilovolts. Essentially this same theory gives the framework for understanding the neutrino induced reactions where the energies are of order 1 to 10 GeV. Since the basic weak interaction proposed by Fermi involves the weak coupling constant G with dimensions of inverse energy squared, we see that his idea of an elementary point interaction has applied to a (dimensionless) coupling constant region where

$$GE_{\beta}^2 = 10^{-15} \quad \text{for } E_{\beta} \approx 10 \text{ KeV}$$

to

$$GE_{\nu}^2 = 10^{-3} \quad \text{for } E_{\nu} = 10 \text{ GeV}.$$

This is indeed quite remarkable. If the elementary Fermi theory were to continue to be true then the effective strength of this "weak" interaction would continue to grow until it became stronger than both electromagnetic and strong interactions. Eventually the continued growth would clash with the principle of unitarity for purely leptonic systems at a c.m. energy of order 300 GeV. (This principle of unitarity is basic to all present understanding of elementary particle theories but has not been experimentally verified at these high energies.)

Further from the point of view of field theory the elementary Fermi theory cannot be a fundamental theory since calculations including the higher orders are badly divergent. Nevertheless, we are faced with the experimental fact that the observed $K_1^0 - K_2^0$ mass difference is roughly second order in the Fermi constant

$$\Delta m = m_K [G m_K^2]^2$$

and thus higher order weak interactions must be present in some fashion.

Physicists are faced here with a puzzle of the type which in the past has led to major new discoveries. A fundamental theory must fail in a region of higher energy but the nature of this breakdown is not yet known.

The elementary Fermi theory even for a semi-leptonic process gives rise to total cross sections which rise linearly with the cm (energy) S as

$$\sigma_{TOT} \approx \frac{G^2 S}{\pi} \quad (1)$$

This behavior is experimentally verified up to the maximum neutrino energies of order 10 GeV. Since the cross section for any process generated by the Fermi interaction must be second order in the weak coupling constant G , a factor having the dimensions of $(\text{energy})^2$ is required. If the energy is sufficiently high with more and more channels opening up then the local character of the four fermion interaction suggests that the total weak cross section will grow as $\sigma \approx G^2 S$. These same considerations apply if the scaling behavior observed in the deep inelastic electron scattering is applied to the weak interactions. The principle of CVC would allow this for the vector current and could reasonably be assumed for the axial current. Thus no masses should be relevant in the asymptotic region and the total cross section should rise as $G^2 S$. This growth continued arbitrarily would mean that the weak interaction with its inherent violation of parity and strangeness would eventually surpass both electromagnetic and strong interactions. Should this not be the case then there must be some kind of deviation from the elementary Fermi

interactions at some energy $\sqrt{S}$. But at what energy? If the weak interaction were to remain smaller than electromagnetic then at an S where

$$\frac{G^2 S}{2\pi} \approx \frac{\pi \alpha^2}{S} \quad (2)$$

or S of order 3200 GeV^2 is the region where deviation from the elementary Fermi theory might occur.

Approximately the same value of S is obtained if one argues that the deviation should occur when the weak matrix element strength becomes comparable to electromagnetic strength, i. e.,

$$\sqrt{8} GS = 4\pi\alpha \quad (3)$$

(The factor $\sqrt{8} = 4/\sqrt{2}$ rather than $1/\sqrt{2}$ would be the natural factor if in the weak Lagrangian the normalized projection operator $(1/2)(1-\gamma_5)$ were used rather than the usual choice of just $(1-\gamma_5)$.)

These values of S are well within the range of the proposed Isabelle project. In fact, the proposed value of $S = 160,000$ allows a value of $GS \approx 1$ where the weak interaction matrix element begins to approach the strength expected for a strong interaction process.

The semi-leptonic inclusive reaction

$$pp \rightarrow e^\pm + \nu + \text{"anything"} \quad (4)$$

is an example of a weak process that is expected to grow linearly with S and that also could have many advantages for detection. In this process the weak interaction would allow the electron to have a large momentum transfer. The other particles composing the "anything" will be confined to small transverse

momentum just as in the usual hadronic interaction and therefore remain along the beam direction. The process becomes extremely simple to detect by the presence of only one lepton (electron or positron) with a very large transverse momentum imbalance, the missing transverse momentum having been carried off by the unobservable neutrino. This fact allows the semi-leptonic reaction to have a very distinctive signal as compared to a hadronic large transverse momentum event since in the hadronic case the momentum imbalance must be cancelled by hadrons of opposite transverse momentum. Thus the missing transverse momentum and energy carried off by the neutrino gives a distinctive character to the semi-leptonic event that should allow for observing that process even in a very substantial background.

Although the reaction (4) does not have as simple an interpretation as the usual semi-leptonic reaction

$$e(\nu)p \rightarrow \nu(e) + \text{anything}$$

in terms of a few form factors, it enjoys the linear rise in S as do all first order weak processes. It is this very fundamental characteristic of the Fermi theory being put to test in reaction (4) and it is just in this context that this reaction could be as suitable as the lepton-induced reaction.

To estimate the cross section for the process (4) a parton model using a point Fermi interaction between leptons and partons is employed. The effect of an intermediate boson W on the distributions and cross sections is included.

The background from large transverse momentum hadrons produced by ordinary hadronic reactions is unknown and could be totally negligible if the fall-off in cross section observed at p_T of order 1 GeV of the form e^{-6p_T}

for $p_T < 3$ GeV and constant for $p_T > 3$ GeV, then the single hadronic event rate is expected to be a factor 10^5 to 10^6 greater than the semi-leptonic reaction. Even for this improbable case the distinctive feature of the semi-leptonic event may allow for its detection. This is because any hadronic event must have transverse momentum conservation while the weak interaction event will have the electron's transverse momentum balanced by the unseen neutrino.

In the next section we show that process (4) will lead to quite measurable counting rates if the luminosity is of order $10^{23} \text{ cm}^{-2} \text{ sec}^{-1}$ and hence could be one of the most significant investigations to be carried out at the Isabelle facility. Either the observation that of a weak interaction growing in strength to surpass the electromagnetic or a breakdown of the Fermi theory would constitute a spectacular and important result having great implications for our understanding of elementary particle physics.

Calculation

It is convenient to use the variables x_1 and x_2 defined as in Berman, Bjorken and Kogut

$$x_1 = -(P_c - P_b)^2 / S$$

$$x_2 = -(P_c - P_a)^2 / S$$

$$S = (P_a + P_b)^2$$

$$x_1 + x_2 \leq 1$$

$$x_1 x_2 = P_T^2 / S$$

where P_c is the four vector of the observed electron and P_a , P_b are the momenta of the colliding initial protons

1) $M_W \rightarrow \dots$

The cross sections are then written as

$$\frac{d\sigma}{dx_1 dx_2} = \frac{G^2 S}{\pi} \left(\frac{s}{Q^2} \right) I(x_1, x_2)$$

The quantity $I(x_1, x_2)$ is an integral over parton and anti-parton distributions as

$$I(x_1, x_2) = \int_{x_1}^{x_2} \frac{dx}{1-x_1} \left[P(x) \bar{P}\left(\frac{x_2 x}{x-x_1}\right) + P\left(\frac{x_2 x}{x-x_1}\right) \bar{P}(x) \right] + x_2 \rightarrow x_1$$

where P and $\bar{P}$ are defined in Appendix B of *NEF* ( ) and are numerically given by

$$P(z_1) = 0.15 (1-z_1)^{7/2} + 1.1 \sqrt{z_1} (1-z_1)^3$$

$$\bar{P}(z_2) = 0.15 (1-z_2)^{7/2}$$

Figure 1 shows $I(x_1, x_2)$ for a range of x_1 and x_2 . For the proposed Isabelle luminosity of $8 \times 10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ $I(x_1, x_2)$ leads to counting rates of order counts per minute.

If the W meson exists then the quantity $I(x_1, x_2) \rightarrow I_\beta(x_1, x_2)$ where

$$I_\beta(x_1, x_2) = \frac{1}{2} \int_{x_1}^{x_2} \frac{\left(\frac{y}{x}\right)^2 dx}{\left[x^2 x_2 - \beta(x-x_1)\right]^2} (x-x_1) \left[P(x) \bar{P}\left(\frac{x_2 x}{x-x_1}\right) + P\left(\frac{x_2 x}{x-x_1}\right) \bar{P}(x) \right] + x_2 \rightarrow x_1$$

and

$$\beta = M_W^2 / S$$

For $\beta < S$ only $4x_1 x_2 < \beta$ is considered since this is the region where kinematics does not allow the decay products of a real W . Figures 2 through 5 show $I_\beta(x_1, x_2)$ for various values of β , x_1 and x_2 . When $\beta > 1$ I_β is seen to depend very weakly on β . While when $\beta \ll 1$ the cross section no longer rises with S but behaves more like $1/S$ as expected.

The actual numerical values of $I(x_1, x_2)$ are quite sensitive to the behavior of the $\nu W_2(x)$ near $x = 1$. If a fit with a $(1-x)$ dependence is used rather than $(1-x)^3$ as in Figures 1-5 then the values of $I(x_1, x_2)$ are quite a bit larger. Probably the fit with $(1-x)^3$ represents a conservative estimate.

$I(x, x_2)$

PP $\rightarrow$ EV + X

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$$\frac{dI}{dx dx_2} = \frac{65.97(1.7)}{\pi 4.22} = 8.6 \times 10^{-1}$$

MODEL

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$$W_2 \approx (1-x)^3$$

K&E SEMI-COMMERCIAL 415 61500 7 CYCLES X 60 DIVISIONS MADE IN U.S.A. KEUFFEL & ESSER CO.

MODEL $\beta = m_H^2/s = .01$

DATE

10^{-4}

10^{-5}

10^{-6}

10^{-7}

10^{-8}

10^{-9}

10^{-10}

10^{-11}

1000000

100000

10000

1000

100

10

1

1 2 3 4 5 6 7 8 9 $\rightarrow x_1$

416 6-460
SEMI-LOGANTHMIC
7 CYCLES X 60 DIVISIONS
EAGLE M.S.A.
REUPPEL & SONNET CO.

MODEL $\beta = .03$

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MODEL $\rho = .05$

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$I(x_1)$

MODEL $\beta = 1.2$

DATE

PP → EVX

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$I(x, \lambda)$

$$\frac{dI}{dx} = \frac{I^2 \pi I(x, \lambda)}{\pi (q)}$$

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MODEL

10^{-1}
 10^{-2}
 10^{-3}
 10^{-4}
 10^{-5}

.1 .2 .3 .4 .5 .6 .7 .8 .9

$v_k = (1-r)$

$I(x, \lambda_2)$

MODEL $\beta = .01$

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$y/2 = (1-x)$