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Interpretation of the new particle of the cosmic ray neutrino experiment

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Abstract. In order to reconcile the life time of the new particle observed in the cosmic ray neutrino experiment with its production rate, it is proposed that the particle has a new quantum number (κ) which may be assigned to leptons and hadrons. In the production of the new particle, assumed to be a heavy charged lepton, κ is conserved by creating an associated lepton-hadron pair. Suppression of the κ-violating interaction is invoked to interpret the long life time of this particle.

Keywords. Cosmic-ray neutrino experiment; heavy lepton; new quantum number.

1. Introduction

The TIFR-Osaka collaboration (Krishnaswamy *et al* 1975*a*) working in the Kolar Gold Mines has recently reported evidence for a special class of neutrino-induced events. These events are characterized by three charged particles coming from the same vertex with large opening angles. The most plausible interpretation of these events is that each of them represents the decay of a new, massive, long-lived particle produced in neutrino or antineutrino collisions within the surrounding rock of the mine. Listed below are the observed properties of the new particle (based on 5 events):

(A) In its decay three charged particles appear with large opening angles.

(B) The ratio of the number of events containing the new particle to the total number of events recorded (which may include other decay modes of new particle) is about 25%.

(C) Estimated cross section for the production of the new particle multiplied by the branching ratio for the observed decay modes, is 10^{-37} cm^2/nucleon.

(D) Mean life time $\tau \geqslant 10^{-9}$ sec.

(E) Estimated mass $M = 2$–5 GeV.

It is clear that more detailed information from the accelerator experiments is needed before one can attempt at a unique explanation of these events induced by the cosmic ray neutrinos. However, an examination of the detailed features of the above mentioned special events allows us to assume that there are no missing neutrals in the decay of the new particles and further the *decay products are all muons*. Thus, in order to fix our ideas we will take the following properties of the new particle for granted: The new particle, to be denoted henceforth by L, is a charged heavy lepton. The heavy lepton L^- (L^+) has the same muonic lepton number as that of the μ^- (μ^+). The rate of L^- production relative to the rate of production in neutrino collisions is given by

$$\frac{\sigma(\nu N \to L^- + \ldots)}{\sigma(\nu N \to \mu^- + \ldots)} \simeq 0{\cdot}25. \tag{1.1}$$

This number may in fact be a lower estimate because no allowance is given to the unobserved decay modes of L. Moreover the observed rate actually refers to both neutrino and antineutrino interactions with matter. However, these reservations apart, it is expected that the estimate (1.1) for the rate is a reasonable guide for our later discussions. The particle L has a mass

$$M \simeq 2 \text{ GeV} \tag{1.2}$$

and decays into three muons

$$L^\pm \to \mu^\pm + \mu^+ + \mu^-. \tag{1.3}$$

Its life time is

$$\tau \simeq 10^{-9} \text{ sec.} \tag{1.4}$$

In seeking an explanation for these new particles there are two crucial features which must be kept in mind; their apparent copious production in neutrino collisions and their long life time. The contradictory nature of these two features is brought out and elaborated upon in section 2. We resolve this probelm of the high production rate coupled with inhibited decay in section 3, by postulating a new quantum number which can be assumed by leptons as well as hadrons. The production of the new particles then proceeds by creating an associated lepton-hadron pair, and decay proceeds by violating the new quantum number. Some simple models of weak interaction which accommodate this new quantum number are presented in section 4. Section 5 summarizes the salient points relating to our explanation of the new particles.

2. Problem connected with the production and the decay of L

In order to ensure the observed rate of production of the new particles as given by eq. (1.1) we assume that L as well as μ are produced in charged-current interactions of neutrinos with rates governed by similar coupling strengths. Thus the production of L must be characterised by a coupling constant which is of the same order as the Fermi coupling constant G.

An estimate of the coupling which controls the decay of the particle L is possible on the basis of the information given in eqs (1.2)–(1.4). Assuming for simplicity, pure V–A coupling for the neutral lepton current interaction which is responsible for the observed mode of decay of L, we have the matrix element

$$\mathcal{M} = \frac{H}{\sqrt{2}} \bar{\mu} \gamma_\lambda (1 + i\gamma_5) L \,.\, l_\lambda \tag{2.1}$$

where

$$l_\lambda \equiv \bar{\mu} \gamma_\lambda (1 + i\gamma_5) \mu \tag{2.2}$$

and H is the coupling constant to be estimated. The rate of decay of L into three muons, neglecting the muon mass compared to the mass M of the particle L, is

$$\Gamma = 2 \cdot \frac{H^2 M^5}{192 \pi^3} \tag{2.3}$$

where the factor 2 arises due to the fact that there are two identical muons in the final state in the decay (1.3). If the 3μ-mode is a dominant decay mode of L we can determine from the observed life time (1.4)

$$\left| \frac{H}{G} \right| \simeq 2 \times 10^{-2} \tag{2.4}$$

where G is the Fermi coupling. If, however, the 3μ-decay is not a dominant one then the value of H is still smaller than the estimate given in (2.4).

Thus while the production of L is characterized by the coupling constant of the order of G, the decay process on the other hand seems to be controlled by a coupling constant which is at least 50 times smaller. It is for this reason we regard the decay of L to be inhibited.

Perhaps it is worth mentioning that this incompatibility between production and decay remains essentially unchanged also for the case when L is identified with a lepton of spin 3/2. To see this we consider the following matrix element.

$$\frac{H'}{\sqrt{2}} \bar{\mu} (f + ig\gamma_5) L_\lambda \cdot l_\lambda \tag{2.5}$$

where l_λ is defined in eq. (2.2), L_λ is the Rarita-Schwinger wave function, f and g are unknown dimensionless constants. As we are dealing with leptons which are assumed to be structureless we regard f and g as mere constants. For the same reason the coupling in (2.5) which does not contain the derivatives of the fields is the only reasonable one.

The formula for the width of L (easily obtainable from the work of Mathews (1965) in his discussion of the semi leptonic decays of Ω^-) is

$$\Gamma = \frac{H'^2 M^5}{960 \pi^3} (f^2 + g^2); \tag{2.6}$$

and in order to reproduce the observed life time we require once again a small coupling strength

$$\left| \frac{H'}{G} \right| (f^2 + g^2)^{\frac{1}{2}} \leqslant 7 \times 10^{-2}. \tag{2.7}$$

We shall not pursue the spin-$\frac{3}{2}$ possibility here any further.

Summarizing this section, the decay process of L is governed by a coupling which is smaller at least by a factor 50 (see eq. 2.4) compared to the coupling that is needed to account for its production.

3. New quantum number κ

In order to reconcile the copious production and the inhibited decay of the new particles observed in the Kolar experiment, we propose a new additive quantum number which will be denoted by the greek letter kappa, κ. This quantum number, instead of being additive, could alternatively be a multiplicative one. For definiteness however, we shall assume that the new quantum number is an additive one. We should emphasize that this is a new type of quantum number which is assigned *both* to leptons and hadrons*.

In the neutrino collisions with nucleons we suppose that the lepton L^- is created in association with a new type of hadron such that the quantum number κ is conserved in the production of the lepton-hadron pair. We shall assume that the lepton L^- is the lightest *particle* carrying a non-zero value (unity, let us say) of the quantum number κ. When the L^- decays into ordinary leptons since the value of κ has to change by one unit we imagine the corresponding decay to be suppressed. The introduction of a new quantum number thus removes the link-up between the production and decay processes of L. The parallel with the original introduction of the strangeness quantum number is evident here, except for the crucial difference that the new quantum number is assigned both to hadrons as well as leptons.

We therefore envisage that in neutrino collisions the production of L is accompanied by the creation of an associated hadron that carries κ, as for instance in the following reactions,

$$\nu + n \rightarrow L^- + B_\kappa^+ \tag{3.1}$$

$$\nu + n \rightarrow L^- + n + M_\kappa^+ \tag{3.2}$$

Here the L^- and the baryon B_κ^+ (meson M_κ^+) have opposite values of κ. If for example the baryon B_κ^+ has a mass of about 3 GeV the threshold for the reaction (3.1) is around a lab energy of 12 GeV.

The observed decay of L is a κ-changing process

$$L^\pm \rightarrow \mu^\pm + \mu^+ + \mu^- \tag{3.3}$$

occurring through a neutral-current interaction. Many other decay modes of L are possible, of which the following are some examples:

$$\begin{aligned} L^- &\rightarrow \pi^- + \nu \\ &\rightarrow \mu^- + e^+ + e^- \\ &\rightarrow \mu^- + \nu + \bar{\nu} \\ &\rightarrow \mu^- + \nu_e + \bar{\nu}_e. \end{aligned} \tag{3.4}$$

All these decays are κ-changing and hence suppressed in the same way as (3.3), although the two-body mode such as $\pi^-\nu$ may be a dominant one. Hence, the value of H/G given in (2.4) may indeed be an over-estimate and the actual value of H/G may be as small as 10^{-3}. This small value further widens the gap between the production mechanism and the decay mechanism.

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* It may be remarked that classification of leptons and hadrons by the same set of quantum numbers is a general feature present in all gauge theories of weak interactions.

Some examples of the decay modes of the κ-carrying hadrons (which must all have masses greater than M) are

$$B_\kappa^+ \rightarrow n + L^+ + \nu \tag{3.5}$$

$$M_\kappa^+ \rightarrow L^+ + \nu. \tag{3.6}$$

Both these decays are κ-conserving and hence are not suppressed.

Thus, the hadron B_κ or M_κ produced in association with L [eqs (3.1) and (3.2)] can decay into a final state again containing an L particle so that on the whole, two new leptons are produced in each neutrino collision, though these may be spatially separated†.

4. Models of weak interaction with κ

We shall now outline two simple models which exhibit the incorporation of the new type of quantum number κ in the theories of weak interaction. For the present, the observation of the long-lived particles discovered by Krishnaswamy *et al* is the only motivation for these considerations. Because of the meagre information available on such particles, the models to be described below will have to be simple and only schematic. Consequently attention will be mainly focussed on the possible directions in which the conventional models can be extended, rather than on constructing models complete in all details.

4.1 *Current-Current Model*

We shall start by constructing the following charged currents J and J^κ, and the neutral currents N and N^κ where the superscript κ signifies a change in the quantum number κ by one unit:

$$J = [(\bar{\mu}\nu) + (\bar{n}p)] \tag{4.1}$$

$$N = (\bar{L}L) + (\bar{q}_\kappa q_\kappa) + [(\bar{\mu}\mu) + (\bar{\nu}\nu) + (\bar{p}p) + (\bar{n}n)] \tag{4.2}$$

$$J^\kappa = (\bar{L}\nu) + (\bar{n}q_\kappa) \tag{4.3}$$

$$N^\kappa = (\bar{L}\mu) + (\bar{p}q_\kappa). \tag{4.4}$$

Here we have suppressed the Lorentz-index and also the display of the V–A structure of the currents. For the sake of simplicity, we have ignored the currents involving e and ν_e as well as the quarks carrying strangeness, charm or such other new quantum number pertaining only to hadrons. The fields p and n may refer to the Gell-Mann-Zweig quarks in which case q_κ refers to the κ-carrying quark with $\kappa = 1$ and charge $= 2/3$. In eqs (4.1) and (4.2) the portions of the current enclosed in square brackets involve ordinary particles—leptons and hadrons having zero κ. One may multiply the new currents appearing in eqs (4.2)–(4.4) by arbitrary real constants but this generality is unwarranted at the present stage.

We now imagine the currents defined in eqs (4.1)–(4.4) to interact with each other. Charge conservation permits the occurrence of only six interactions of

† It is reassuring to note that the new event (called event No. 6) observed in the same Kolar Gold Mines experiment (Krishnaswamy *et al* 1975*b*) provides support to such a hypothesis, although it must be emphasized that the interpretation of this event is by no means unique.

the current-current form which shall be classified for convenience into two groups: the first group of interactions conserves the quantum number κ and the second group violates κ by one unit;

$$\mathcal{L} = \frac{G}{\sqrt{2}}\,[JJ^\dagger + NN^\dagger + J^\kappa (J^\kappa)^\dagger + N^\kappa (N^\kappa)^\dagger] \tag{4.5}$$

$$\mathcal{L}^\kappa = \frac{H}{\sqrt{2}}\,(J^\kappa J^\dagger + N^\kappa N^\dagger + \text{h.c.}). \tag{4.6}$$

In writing these effective Lagrangians* we have for simplicity chosen the Fermi coupling G to be common for all the $\triangle\kappa = 0$ interactions, and introduced another common coupling constant H for the $\triangle\kappa = 1$ transitions.

By virtue of the third term in eq. (4.5) the neutrino production of L is thus ensured to occur roughly at the observed rate given by eq. (1.1). In order to account for the observed life time of L through the κ-changing interaction (4.6) we should have, using eq. (2.4),

$$\left|\frac{H}{G}\right| \simeq \frac{1}{50} \tag{4.7}$$

The suppression of the off-diagonal interactions given in eq. (4.6) relative to the diagonal interactions in eq. (4.5) is a natural feature in an intermediate boson model which we shall now proceed to construct.

4.2 *Intermediate Boson Model*

We use the same currents defined in eqs (4.1)–(4.4) but couple each of these currents to a different intermediate boson:

$$\mathcal{L}_{\text{int}} = g\,[(J\tilde{U} + h.c.) + (J^\kappa \tilde{V} + h.c.) + N\tilde{X} + (N^\kappa \tilde{Y} + h.c.)] \tag{4.8}$$

The bosons $\tilde{U}$, $\tilde{V}$ and their hermitian conjugates mediating the charged-current interactions are charged, while the bosons $\tilde{X}$, $\tilde{Y}$ and $\tilde{Y}^\dagger$ mediating the neutral-current interactions are neutral. We have used the same semiweak coupling constant g for all the interactions, for simplicity.

We assign $\kappa = 0$ for the bosons $\tilde{U}$, $\tilde{U}^\dagger$ and $\tilde{X}$ which couple to the κ-preserving currents (these bosons are conventionally denoted by the symbols $W^\pm$ and Z), and assign $\kappa = -1$ for $\tilde{V}$ and $\tilde{Y}$ which couple to the κ-changing currents. Thus the interaction given by eq. (4.8) conserves κ exactly. Note that we have assumed the κ-preserving neutral current N to be self-conjugate so that the boson $\tilde{X}$ ($\kappa = 0 =$ charge) also is self-conjugate.

We now envisage the breaking of strict κ-conservation by allowing for mixing between the states of bosons with different values of κ but equal charge. First let us consider the mixing between the states of the charged bosons $\tilde{U}$ and $\tilde{V}$. As a result of mixing, let the physical particles denoted by U and V (with well-

* Symmetrisation with respect to J and $J^\dagger$, N and $N^\dagger$ etc. is understood.

defined masses) be given by

$$\tilde{U} = U \cos\theta - V \sin\theta$$

$$\tilde{V} = U \sin\theta + V \cos\theta \tag{4.9}$$

where θ is an unknown mixing angle.

In the case of the neutral bosons, we have to consider two kinds of mixing. First, $\tilde{Y}$ and $\tilde{Y}^\dagger$ have to be mixed to form CP-eigenstates denoted by $\tilde{Y}_1$ and $\tilde{Y}_2$.

$$\tilde{Y}_1 = \frac{1}{\sqrt{2}}(\tilde{Y} + \tilde{Y}^\dagger), \quad \tilde{Y}_2 = \frac{1}{\sqrt{2}\mathrm{i}}(\tilde{Y} - \tilde{Y}^\dagger). \tag{4.10}$$

Only one of these (namely the one with the same CP-eigenvalue as that of $\tilde{X}$) will mix with the state $\tilde{X}$. Choosing this to be the state $\tilde{Y}_1$ we define, using another mixing angle ϕ, the physical particles to be X and Y_1

$$\tilde{X} = X \cos\phi - Y_1 \sin\phi$$

$$\tilde{Y}_1 = X \sin\phi + Y_1 \cos\phi \tag{4.11}$$

Rewriting the eq. (4.8) in terms of the physical states of the intermediate bosons we get

$$\mathcal{L}_{\text{int}} = g\,[(\cos\theta J + \sin\theta J^\kappa)\,U + (-\sin\theta J + \cos\theta J^\kappa)\,V + h.c.]$$

$$+ g\,[(\cos\phi\, N + \sin\phi\, N_1^\kappa)\,X + (-\sin\phi\, N + \cos\phi\, N_1^\kappa)\,Y_1 + N_2^\kappa\,\tilde{Y}_2] \tag{4.12}$$

where we have defined

$$N_1^\kappa = \frac{1}{\sqrt{2}}(N^\kappa + N^{\kappa\dagger}), \quad N_2^\kappa = -\frac{1}{\sqrt{2}\mathrm{i}}(N^\kappa - N^{\kappa\dagger}). \tag{4.13}$$

In the limit of large masses of the bosons, eq. (4.12) can be recast to yield the following effective Lagrangian:

$$\begin{aligned}\mathcal{L}_{\text{int}} = g^2 \Bigg[&\left(\frac{\cos^2\theta}{m_U^2} + \frac{\sin^2\theta}{m_V^2}\right) JJ^\dagger + \left(\frac{\cos^2\phi}{m_X^2} + \frac{\sin^2\phi}{m_{Y_1}^2}\right) NN^\dagger \\ &+ \left(\frac{\sin^2\theta}{m_U^2} + \frac{\cos^2\theta}{m_V^2}\right) J^\kappa J^{\kappa\dagger} + \left(\frac{\sin^2\phi}{m_X^2} + \frac{\cos^2\phi}{m_{Y_1}^2}\right) N_1^\kappa N_1^\kappa \\ &+ \frac{1}{m_{Y_2}^2} N_2^\kappa N_2^\kappa \\ &+ \left(\frac{1}{m_U^2} - \frac{1}{m_V^2}\right) \cos\theta \sin\theta\, (J^\kappa J^\dagger + h.c.) \\ &+ \left(\frac{1}{m_X^2} - \frac{1}{m_{Y_1}^2}\right) \cos\phi \sin\phi\, N_1^\kappa N \Bigg]. \end{aligned} \tag{4.14}$$

We have thus recovered the current-current model of section (4.1), with the off-diagonal interactions $J^\kappa J^\dagger$ and $N_1^\kappa N$ appearing with a strength weaker than that of the interactions diagonal in the κ-indices. In each of the last two terms of eq. (4.14) there are two factors which tend to suppress the off-diagonal terms; the factor associated with the mixing angles and the factor involving masses wherein the contributions from the two bosons occur with opposite signs.

Denoting the typical values of the mass of the bosons by m and the mass-difference among them by $\triangle m$, we require

$$\frac{H}{G} \simeq \cos\phi \sin\phi \frac{2\triangle m}{m} \simeq \frac{1}{50} \tag{4.15}$$

in view of the estimate eq. (2.4). Thus one can even get the required suppression of the coupling without the necessity of invoking small mixing angles; for instance by choosing

$$\phi \simeq 45°, \quad m \simeq 50 \text{ GeV}. \quad \triangle m \simeq 1 \text{ GeV}.$$

We may remark that the terms $N_1^\kappa N_1^\kappa$ and $N_2^\kappa N_2^\kappa$ appearing in eq. (4.14) allow $\triangle\kappa = 2$ processes of strength which may be comparable to the usual weak interaction. This is a special feature of the present intermediate boson model.

5. Summary and discussion

The underground neutrino experiment at Kolar Gold Mines seems to provide evidence for a new type of charged lepton. The new lepton L is heavy and relatively stable against ordinary weak interactions. In an effort to reconcile the observed rate of production of these new leptons with their long life-time, we have suggested the existence of a quantum number denoted by κ which is approximately conserved in weak interactions and which should be assigned both to leptons and hadrons.

In the events in which $L^\pm$ is produced in the Kolar experiment, according to our suggestion therefore, there should be an associated hadron which carries the same quantum number with opposite sign. The decay of $L^\pm$ proceeds by a violation of the quantum number and hence is hindered. An important assumption in the above strategy of course is the absence of κ-carrying hadrons or leptons lighter than the leptons $L^\pm$, so that κ-conserving decays of $L^\pm$ are kinematically forbidden. This obviously eliminates the possibility that κ is the strangeness quantum number. It should also be remarked that the quantum numbers such as charm are usually assigned to only hadrons and hence should be distinguished from the quantum number κ.

It is possible that there exists also a κ-carrying neutral lepton L° which is heavier than L. If the dominant decay modes of L° include those involving two oppositely charged leptons (*e.g.* $L^\circ \to \mu^-\mu^+\nu$, $e^-e^+\,\nu$, $\mu^-\,e^+\,\nu_e$, $L^-\,e^+\,\nu_e$), then it is likely that the production of L° is contributing to the recently reported dimuon events and other dilepton events (see Albright 1975).

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Note added

We would like to add that there is also the possibility that one of the decay products of L is an electron in which case we should re-interpret L as a heavy lepton carrying electron-lepton number and undergoing the decay $L^{\pm} \rightarrow e^{\pm} + \mu^{+} + \mu^{-}$ (instead of the decay assumed in eq. (1.3)). The $L^{\pm}$ should then be interpreted as being produced in interactions of ν_e or $\bar{\nu}_e$ within the rock of the mine. This explanation may have an advantage: since the flux of electron-neutrinos is smaller than the flux of muon-neutrinos in accelerators one may understand why the $L^{\pm}$ were not observed so far in accelerator experiments. In cosmic rays, on the other hand, the relative fluxes of ν_e and $\bar{\nu}_e$ are not small. However, our interpretation of the experimental observations in terms of a new quantum number clearly remains unaltered whether L is a heavy lepton of the muon-type or the electron-type. Only minor changes are needed in the models of sec. 4. We thank B V Sreekantan for a discussion relating to this point.