Heavy-Lepton-Cascade Interpretation of the Neutrino-Induced Trimuon Events*

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The experimental data on neutrino-induced trimuon production are compared with the results of a cascade model involving two heavy leptons. The agreement between theory and experiment is excellent.

The Fermilab-Harvard-Pennsylvania-Rutgers-Wisconsin (FHPRW) group has observed six $\mu^-\mu^-\mu^+$ events produced in neutrino interactions[1] and measured the muon momenta in five of them. Two events were seen previously in the Caltech-Fermilab experiment.[2] The FHPRW group has made a careful analysis of these trimuon events[3] and compared them with their previous dimuon events.[4] Almost all $\mu^-\mu^+$ events are compatible with the hypothesis that the prompt μ^- is produced at the neutrino vertex while the μ^+ is a decay product[5] of new charmed[6] hadrons. However, an explanation of the $\mu^-\mu^-\mu^+$ events based on charmed-particle semileptonic decays[3] gives unsatisfactory fits to the data. After discussing several alternative possibilities, the FHPRW group suggests that the $\mu^-\mu^-\mu^+$ events, together with the $\mu^-\mu^-$ events, and some of the $\mu^+\mu^-$ events, arise from a new phenomenon, namely a heavy-lepton-cascade decay. In particular, they propose the existence of at least two heavy leptons, called M and L with masses 7^{+3}_{-1} and $3.5^{+1.5}_{-0.4}$ GeV/c^2, respectively. The trimuons then arise from the decay chain $\nu_\mu + N \to M + X$, $M \to \mu + L +$ (neutrino), and finally $L \to \mu + \mu +$ (neutrino). The precise relationship of M and L to the heavy lepton observed by Perl *et al.*[7] is unclear. There is no evidence that a charged lepton with mass around 2 GeV/c^2 is directly produced in ν_μ interactions.[8]

In this Letter we take up the suggestion that the trimuon events can be explained by a heavy-lepton-cascade hypothesis. We construct a simple model and compare the theoretical predictions for various distributions with the data published in Refs. 1 and 3. We assume the existence of two heavy leptons, M^- and L^0, which have charged-current $V-A$ couplings to the known leptons. The production of the M in the reaction $\nu_\mu + N \to M + X$ has been considered previously by several authors,[9] who have given cross sections based on the structure functions of the quark parton model. Our assumption that the L^0 has only charged-current couplings means that we forbid the reaction $\nu_\mu + N \to L^0 + X$, which would otherwise lead to too many opposite-sign dimuon events.[10] The heavy M^- has decay modes $M^- \to L^0 + \bar{\nu}_\mu + \mu^-$, $L^0 + \bar{\nu}_e + e^-$, $L^0 + X$, and $\nu + X$. Then the L^0 can decay via the model $L^0 \to \mu^- + \nu_\mu + \mu^+$, $\mu^- + \nu_e + e^+$, and $\mu^- + X$. Such decays lead to events with one, two, or three muons. We concentrate here on a phenomenological analysis of the $\mu^-\mu^-\mu^+$ final state where one prompt μ^- is produced in the $M^- \to L^0$ transition and the other pair comes from the L^0 decay. We note here that this type of model has two obvious consequences. First, because all three muons are produced from the cascade decay of the M^-, where the production and decay are relatively independent (up to small spin-spin corrections), the trimuon and dimuon invariant masses should not show any dependence on the energy of the neutrino beam. Second, all decays involve at least three particles so that no invariant mass should peak at a unique value. Also, the absence of the neutral-current decay $M^- \to \mu^- + \mu^+ + \mu^-$ implies the absence of a peak in the trimuon invariant mass. We first give a short discussion of our calculation, followed by a presentation of the results. A more detailed paper, which will include a discussion of semileptonic decays involving hadrons and dimuon final states will follow later.

The calculation can be split into two parts, namely the production and the decay. We know that the M^- polarization is important in certain kinematical regions,[9] so we calculate the square of the complete matrix element for the reaction

$\nu_\mu + N \to M^- + X$ followed by the decay $M^- \to L^0 + \bar{\nu}_\mu + \mu^-$, keeping all spin effects, all terms in the M^- and L^0 masses, and taking the coupling constant at the production vertex to be ϵG_F, with $\epsilon = 1$. Then, because the L^0 polarization will be very small, we complete the decay chain by adding the square of the matrix element for the unpolarized L^0 decay $L^0 \to \mu^- + \nu_\mu + \mu^+$. The narrow-width approximation is used for both the M^- and the L^0 particles. Hence our final results need to be multiplied by three factors: ϵ^2, the square of the suppression factor (mixing angle) at the production vertex; the branching ratio B_1 for the decay $M^- \to L^0 + \bar{\nu}_\mu + \mu^-$; and the branching ratio B_2 for the decay $L^0 \to \mu^- + \nu_\mu + \mu^+$. We assume the mass of the M^- to be 8 GeV/c^2, and the mass of the L^0 to be 4 GeV/c^2.

The total rate is found by folding the production cross section with the *normalized* neutrino flux for quadrupole-triplet focusing and gives the answer 5×10^{-38} cm^2. Actually only the portion of the neutrino spectrum above 80 GeV is effective due to the heavy mass of the M^-. It is remarkable that the effect of the falling spectrum is almost exactly balanced by the rising production cross section over a wide range of neutrino energies. The maximum in the flux-times-cross-section plot is obtained with $E_\nu = 175$ GeV and has only decreased by a factor of 8 at $E_\nu = 300$ GeV. To get a feeling for this number 5×10^{-38} cm^2, we note that the corresponding number for regular neutrino interactions making single-μ^- events is 66×10^{-38} cm^2, for $E_\nu > 50$ GeV. Hence the production of the M particle, if taken at full strength, is ~8% of the μ^- cross section in the energy region $E_\nu > 50$ GeV. Folding in the neutrino spectrum does not change the differential distributions in any significant way, so we give our results for a fixed beam energy $E_\nu = 200$ GeV. This means that event No. 119, which has a total visible energy of 249 GeV and is included in our plots, should be given a relatively low weight. We have checked our hadron energy distributions to see that such an event is possible when we take the neutrino spectrum into account. However, its probability is exceedingly small.

The primary source of ambituity in comparing our results with the data is the μ^- identification problem. In order to distinguish carefully between the theoretical results, where we know which vertex the muons come from, and the experimental results, where the like-sign muons are indistinguishable, we call the prompt muon at the first decay μ_A^-, and those at the second decay μ_B^- and μ_3^+. In our Monte Carlo calculation of the twelve-dimensional integral for $\sigma B_1 B_2$ we can simulate the experimental situation by ordering the momentum of the muons accordingly, depending on whichever μ^- particle has the larger energy. Then we call μ_1 the fast μ^-, μ_2 the slow μ^-, and μ_3 the μ^+ (to conform with the notation in Ref. 1).

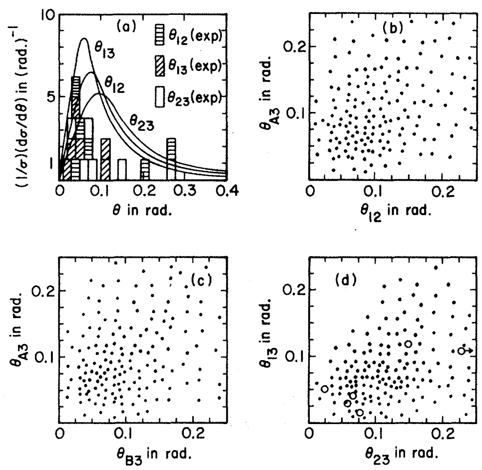

FIG. 1. (a) The trimuon spectra in the opening angles (in radians). The boxes show the distribution of the experimental values according to the different choices for the angles. (For errors see Ref. 1.) (b)–(d) Scatter plots of the opening angles (in radians). The first two plots show the theoretical distributions, Our Monte Carlo results, which can be compared with the data points (circles), are shown in (d).

In Fig. 1(a) we give the theoretical opening-angle distribution $\sigma^{-1}d\sigma/d\theta$ for $\theta_{AB} \equiv \theta_{12}$ (which is almost identical to the distributions in θ_{B3} and θ_{A3}), and the distributions in θ_{13} and θ_{23}. The angles are given in radians and we also show the experimental values for θ_{12}, θ_{13}, and θ_{23} as boxes. The experimental errors are not shown, but they are given in Ref. 1. Two-dimensional scatter plots in the opening angles θ_{A3} vs θ_{12}, θ_{A3} vs θ_{B3}, and θ_{13} vs θ_{23} are shown in Figs. 1(b)–1(d), respectively. The first two plots are almost symmetrical about the diagonal. The last diagram shows that the angle between the fast μ^- and the μ^+ is on the average smaller than the angle between the slow μ^- and the μ^+. This effect is clearly present in the data which are marked on Fig. 1(d).

The trimuon invariant-mass spectrum in $M_{AB3} = M_{123}$ is shown in Fig. 2(a), and the five experimental values are also shown as boxes (without error estimates). Pairing the possible dimuon

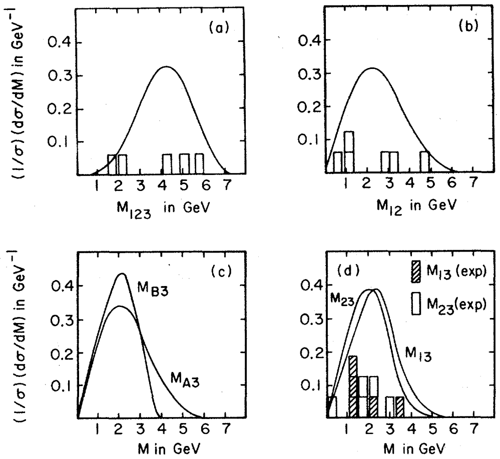

FIG. 2. (a) The trimuon invariant-mass spectrum. We give the experimental values as boxes. (For errors see Ref. 1.) (b)–(d) Spectra in the invariant masses of the muon pairs. The effect of ordering the momenta is to convert (c) into (d).

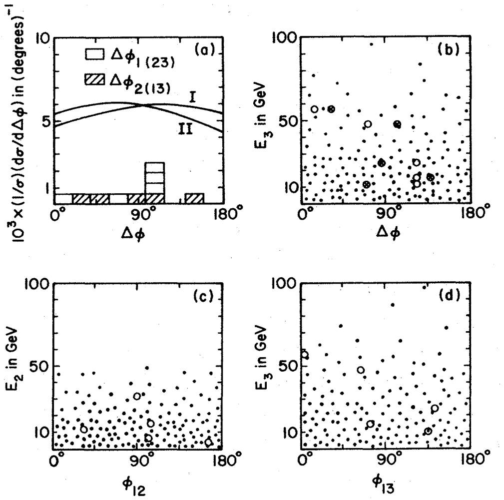

FIG. 3. (a) The differential cross section in the angle $\Delta\varphi$. Curves I and II refer to the ambiguity in choosing the μ^- momentum. $\Delta\varphi_{1(23)}$ refers to the angle between μ_1^- and the resultant formed from μ_2^- and μ_3^+. (b) Scatter plot of $\Delta\varphi$ vs E_3, the energy of the μ^+. The open circles give $\Delta\varphi_{1(23)}$ and the others $\Delta\varphi_{2(13)}$. (c) Scatter plot of φ_{12} vs E_2, the energy of the slow μ^-. (d) Scatter plot of φ_{13} vs E_3, the energy of the μ^+.

combinations leads to spectra in $M_{AB} \equiv M_{12}$ [Fig. 2(b)], M_{A3} and M_{B3} [Fig. 2(c)], and M_{13} and M_{23} [Fig. 2(d)]. The experimental values for M_{12}, M_{13}, and M_{23} are also given (again without error estimates). Obviously there is good agreement between the predictions of the theory and the experimental results. The M_{123} and M_{B3} spectra peak around one-half the value of the M^- and L^0 masses, respectively. Theoretically, the average value of M_{13} is slightly larger than the average value of M_{23}. This effect is difficult to see in the data because the errors are so large.

We now discuss several angles between the muon momentum vectors projected on a plane perpendicular to the beam direction. If we form the resultant of the vectors for μ_B^- and μ_3^+, then we define $\Delta\varphi$ to be the angle between that vector and the direction of μ_A^-. The spectrum in $\Delta\varphi$ is shown in Fig. 3(a) as curve I. Curve II shows the spectrum in the same opening angle with the exchange of μ_A^- and μ_B^-. If we average these two distributions, then we fake the experimental situation. Hence we show the five events for both choices of $\Delta\varphi$. In Fig. 3(b) we show a scatter plot of $\Delta\varphi$ vs E_3. The plot should be compared with Fig. 2(a) in Ref. 3 to show the difference between the lepton-cascade-decay model and the charm-decay model. We do not show plots for $\Delta\varphi$ vs E_A or E_B because they are almost identical to those in Fig. 3(b).

We now define φ_{12} as the angle between the projections of the two μ^- vectors. We present a scatter plot of this angle versus E_2 in Fig. 3(c). The distribution of points is uniform in φ_{12}. This contrasts with the charmed-hadron-decay model in which the events are concentrated in the region of large φ_{12} and small E_2 [see Fig. 2(b) in Ref. 3]. Another angle which is useful in distinguishing between models is φ_{13}, the angle between the projections of the fast μ^- and the μ^+. A scatter plot of this angle versus E_3 is shown in Fig. 3(d). All these plots show that there is no appreciable peaking in $\Delta\varphi$, φ_{12}, or φ_{13}. The reason is that hadrons and undetected neutrinos are taking away some of the momentum transfer and these vectors balance each other. The peaking near $\Delta\varphi = 180°$ in the charmed-hadron-decay model reflects the balance in the transverse momenta between the prompt μ^- and the hadron jet.[3]

We conclude that there is no problem in interpreting the six $\mu^-\mu^-\mu^+$ events as the decay products of heavy leptons. Hence if we know values for the branching ratios B_1 and B_2, we can use the total event rate to find the mixing angle at the production vertex. One problem here is that many muons in the lepton-cascade-decay model are slow and therefore escape detection or are classified as single-muon or dimuon events. In fact, if we impose momentum cuts of 5 GeV/c for all three muons, the theoretical value of $\sigma B_1 B_2$

goes down by 30%. If we compare the uncorrected experimental number 5×10^{-4} for $R=\sigma(\mu^-\mu^-\mu^+)/\sigma(\mu^-)$, with $E_\nu > 100$ GeV, we note that $\sigma(\nu_\mu + N \to M^- + X)/\sigma(\nu_\mu + N \to \mu^- + X)$ is 14% for our model with the same energy cut. Model-dependent but reasonable estimates[12] for the two branching ratios are in the range 7 to 15%, yielding $R=(7-30)\times 10^{-4}$. The agreement between these values sugfests that there is little room for a mixing angle at the production vertex. In other words, the leptonic vertex couples the ν_μ-M^- left-handed with a new charged gauge boson (not the regular W^+). Finally we point out that while the heavy-lepton-cascade chain will lead to some excess of events at large y in the reaction $\bar{\nu}_\mu + N \to \mu^+ + X$, it is clear that the magnitude of this contribution is much too small to explain the whole effect.

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Lepton-Cascade-Decay Interpretation of Neutrino-Produced Trimuons*

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We explain neutrino-produced trimuon events with a gauge model incorporating heavy leptons M^- and M^0 with the cascade-decay chain $M^- \to M^0\mu^-\bar{\nu}$ and $M^0 \to \mu^-\mu^+\nu$. Comparisons with trimuon data are made for M^- and M^0 masses 7 and 3.5 GeV, respectively. This mechanism predicts same-sign dimuons at five times the trimuon rate.

Energetic trimuon events have recently been observed in neutrino experiments.[1,2] The rate and kinematics of these events seem incompatible with dilepton production at the hadron vertex, e.g., from associated charm production. In this Letter we show that all characteristics of the trimuon events can be understood in a gauge-theory model which includes M^- and M^0 heavy leptons of masses 7 and 3.5 GeV, respectively. The essential feature of this interpretation is neutrino-production of M^-, which then decays via

$$M^- \to M^0\mu_1^-\bar{\nu}, \quad M^0 \to \mu_2^-\mu_3^+\nu. \qquad (1)$$