Investigations of Neutrino Interactions with Two Muons in the Final State*

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We have observed the reaction $\nu+N\to\mu+\mu+$hadrons at high energies. The approximate rate for these events is ~1% of that for the reaction $\nu+N\to\mu^-+$hadrons, at $E_\nu\sim150$ GeV.

Neutrino events with two muons in the final state ($\nu+N\to\mu+\mu+X$) have been observed in two detectors at Fermilab.[1] We report here on investigations of 2μ events detected in the California Institute of Technology–Fermilab experiment (e.g., see Fig. 1). The data were obtained in the Fermilab narrow-band beam.[2]

Several aspects of our experiment relevant to this search should be pointed out. The apparatus consists of a 1.5-m×1.5-m Fe target with scintillation counters (for determining the hadron energy, E_h)[3] interspersed every 10 cm of Fe and spark chambers (for tracking muons) every 20 cm of Fe. Muons are identified by penetration (as particles penetrating ≳2 m of Fe). An important attribute of our apparatus for this search is the distributed target of high density. The average density ($\rho\sim4$ g/cm^3) minimizes the primary background source of extra muons from nonprompt decays of hadrons ($\pi\to\mu\nu$ and $K\to\mu\nu$). Following this neutrino target-detector is a 1.5-m-diam toroidal magnet, which is used to determine the sign and the energy (E_μ) of muons to ~±20%. The small aperture of this magnet represents a major limitation in the data reported here. Large-angle muons miss the magnet and therefore the momentum and sign of the muons are not determined for all of the identified 2μ events.

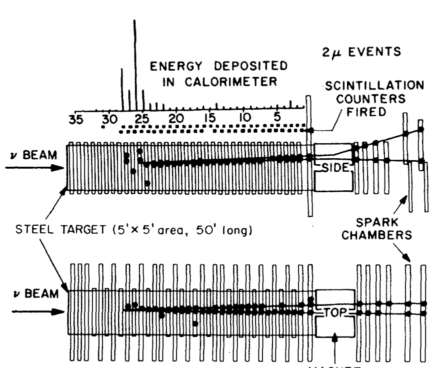

FIG. 1. A 2μ neutrino interaction in the Caltech-Fermilab detector. Note that the vertical and horizontal scales are different.

From neutrino runs, we observed 2355 single-μ neutrino interactions (1μ) and 19 events with two μ's while for antineutrino runs we observed 388 single-μ interactions and two events with two μ's. In order to estimate backgrounds and understand experimental biases most reliably, we only report on events where the "right-sign" muon (μ^- for ν's and μ^+ for $\bar{\nu}$'s) traversed the magnet. This leaves a sample of eight 2μ events for ν's and two events for $\bar{\nu}$'s. Since the antineutrino events do not represent a statistically significant sample, we concentrate here only on the neutrino data.

We have investigated in some detail whether these 2μ events can be explained from known sources. The most serious background source is expected to be single-μ neutrino interactions with subsequent production of an extra muon from decays of known final-state mesons (i.e., π's and K's). Our estimate of the number and energy spectrum for muons resulting from these "nonprompt" sources is shown in Fig. 2. The calculation of this background involved folding the *measured* E_h distribution for single-μ events with a *calculated* probability spectrum of decay muons, taking into account the detection efficiency of our apparatus.

The probability spectrum was calculated assuming the final-state hadron distributions for $\nu+N\to\mu+X$ to be the same as in $\pi+N\to X$ at equivalent E_X. Recent bubble-chamber data indicate that the distributions of hadronic secondaries from neutrinos are within a factor of 2 of our assumptions.[4] Our calculation in addition followed the development of subsequent interactions in the

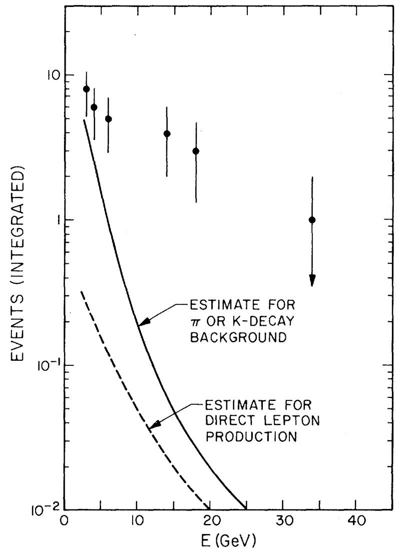

FIG. 2. Comparison of the observed energies of the extra muon in 2μ interactions with that expected from the 1μ events having subsequent π or K decays or direct production of leptons from produced hadrons.

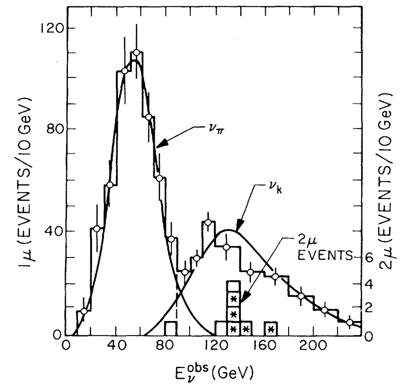

FIG. 3. The total observed energy in 1μ neutrino interactions ($E_\nu^{obs} = E_{\mu^-} + E_h$) compared to that in 2μ events ($E_\nu^{obs} = E_{\mu^-} + E_h + E_{\mu^+}$ for events marked by an asterisk and $E_\nu^{obs} = E_{\mu^-} + E_h + P_{\mu'}$ for the other three events for which only a lower limit on the second muon energy is determined).

calorimeter yielding more (but lower energy) π's and K's and the corresponding decay probabilities.

The measured distributions of the extra-muon energies in neutrino-induced 2μ events are compared in Fig. 2 with the calculated distributions for events originating from decays. The comparison indicates that the events with a high-energy extra muon are probably not from decays. For example, there are four observed 2μ events with $E_{\mu^+} > 14$ GeV, while only ~ 0.07 are expected from decays. We emphasize that we cannot rule out the possibility that all the events come from π or K decay from our data alone.[5] However, to explain our data, final-state hadron distributions in neutrino interactions would have to contain many more fast pions than indicated by recent bubble-chamber results.[4]

We also have investigated the possibility that the 2μ events are a result of direct lepton production by final-state hadrons in subsequent interactions in the calorimeter. In this calculation we assumed that the μ/π ratio in hadron collisions is 10^{-4} for *all* incident- and final-state energies.[6] We estimate from our calculation that for $E_{\mu^+} > 14$ GeV the expected level from this source is $\lesssim 0.03$ event. The calculated spectrum expected from direct lepton production is shown in Fig. 2.

We will now describe some features of these apparently anomalous events. The total observed energies, $E_\nu^{obs} = E_{\mu^-} + E_h + E_{\mu^+}$ for the five 2μ events where the extra muon energy is measured (marked by an asterisk) and $E_\nu^{obs} = E_{\mu^-} + E_h + P_{\mu'}$ for the remaining three events, are shown in Fig. 3. $P_{\mu'}$ represents a lower limit on the momentum of the second muon determined by range for those events where it misses the magnet. The observed energies of the five 2μ events in which the energies of both μ's have been measured are close to the mean energy of ν_K neutrinos (≈ 150 GeV). However, more statistics are necessary to ascertain whether missing energy is carried off by a final-state neutrino (as required by lepton conservation). No peak is apparent in the invariant mass distribution of the 2μ system; thus it is improbable that the events originate from the production of a narrow resonance decaying into $\mu^+\mu^-$. In four of the five events both charges are determined and all have oppositely charged muons and $E_{\mu^-} > E_{\mu^+}$.

We calculate the kinematic variables in an analogous way to those in single-μ interactions by assuming that the "right-sign" muon (e.g., μ^- for ν_μ incident) is associated with the neutrino vertex; i.e., $E_h = E_\nu - E_{\mu^-}$, $y = E_h/E_\nu$, $Q^2 = 4E_\nu E_{\mu^-} \times \sin^2(\theta/2)$, $x = Q^2/2ME_h$, and $W^2 = M^2 + 2ME_h - Q^2$. For one ambiguous event we calculate the kinematics under both assumptions $E_\nu = 150$ GeV (ν_k) and $E_\nu = 82$ GeV (ν_π) (see Fig. 4). We note that the observed 2μ events tend to have large invariant mass W recoiling against the μ^-, while the mean observed x seems to be typical of that for single-muon events ($\langle x\rangle_{2\mu} \sim 0.19$ versus $\langle x\rangle_{1\mu} \sim 0.16$).

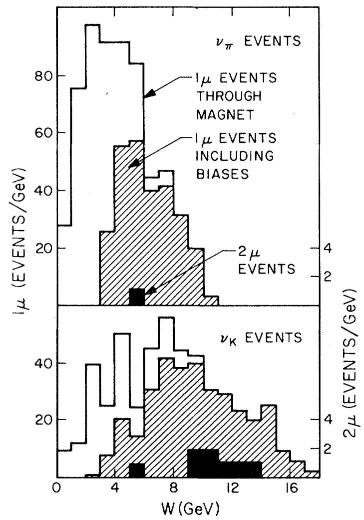

FIG. 4. The distribution of the invariant mass W recoiling against the μ^- in 1μ and 2μ neutrino interactions. The shaded area included the expected bias because of geometrical requirements involved in the detection of the second muon (see text).

The measured distributions for the 2μ events are influenced by the detection efficiency for the second muon. In the calculation of this efficiency, a model for the production of two μ's must be assumed. For example, if the extra muon results from the decay of a state produced at the hadron vertex, then the geometrical requirement that the second muon penetrate $\geqslant 2$ m of steel before it leaves the apparatus introduces an inefficiency in the detection of events for which the direction of the momentum of the final-state hadron system is at a large angle. This is illustrated in Fig. 4 which shows the W distribution for all single-μ events in which the μ^- traversed the magnet and those satisfying the additional requirement that the direction of the mean final-state hadron momentum is such that a muon emitted in that direction would traverse $\geqslant 2$ m of steel before exiting from the apparatus.

In conclusion, we have observed 2μ events produced in neutrino interactions which do not appear explainable by a nonprompt source.[5] The observed rates are $\gtrsim 1\%$ at $\langle E_\nu \rangle \sim 150$ GeV ($\geqslant 5$ two-muon events compared to 329 single-muon events). When these 2μ rates are compared with a recent limit on the ratio of 2μ to 1μ events of Asratyan[7] ($\leqslant 10^{-3}$ for $\langle E_\nu \rangle \approx 15$ GeV), it appears that the level increases with energy, indicating a threshold or a steeper than linear energy dependence.

New physics possibilities include the production and decay of a neutral heavy leptons or of new hadrons (e.g., charm). At present, there is not enough information from our data to ascertain whether the 2μ events are a phenomenon to be associated with the neutrino vertex, hadron vertex, or both. Studies of the kinematic properties of a larger statistical sample of 2μ events can distinguish between the various possibilities,[8,9] provided that the experimental biases are understood and the distribution and number of events originating from π and K decays are known at the 5% level.[10] For example, a very large E_{μ^-}/E_{μ^+} ratio for ν-induced 2μ events tends not to favor neutral heavy-lepton production.

Although the sources of 2μ events are not yet clear, it appears almost certain that some new phenomenon has been observed. Information from our experiment on energy dependence and production by antineutrinos should be available soon.

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