Observation of New-Particle Production by High-Energy Neutrinos and Antineutrinos*

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We have observed fourteen events in which two muons are produced by high-energy neutrino and antineutrino interactions. The absence of trimuon events and the observed characteristics of the dimuon events require the existence of one or more new massive particles that decay through the weak interaction. The new particle mass is estimated to lie between 2 and 4 GeV.

We have previously reported two candidates for dimuon production by neutrinos.[1] Subsequently, twelve additional events have been observed and are reported here. The characteristics of production, which will be discussed in greater detail later,[2] are consistent with a new particle of mass less than or near 4 GeV. Evidence against the decays of charged pions and kaons as the source of the second muon is provided by (i) the rate of dimuon events, (ii) the opposite signs of their electric charges, (iii) the different densities of the target materials in which they were produced, and (iv) the distributions in muon momentum and transverse momentum.

The experimental method makes use of several features of the liquid-scintillator calorimeter, magnetic-spectrometer detector previously reported.[3,4] Events produced either in the liquid or in a block of iron, with two particles in time coincidence which penetrate at least 1.2 m of iron, are selected. One such event is shown in Fig. 1. The momentum and angle of each muon is measured and extrapolated back into the target. The

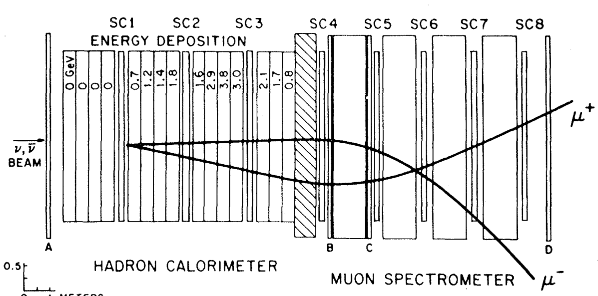

FIG. 1. Sketch of a muon-pair event which starts in module 5 of the ionization calorimeter and deposits 21.8 GeV ionization energy. The muon momenta are $p_{\mu^+} = 14.7$ GeV and $p_{\mu^-} = 8.4$ GeV.

longitudinal position at which an interaction in the calorimeter occurs can also be determined by the pulse-height distribution in the calorimeter. The distance of approach Δ of the two rays at the approximate longitudinal position of the interaction that triggered the event was obtained for every dimuon candidate. The distribution is shown in Fig. 2(a). Two further requirements were made on the sample: (i) The vertex of the event defined as the (x, y, z) position at the dis-

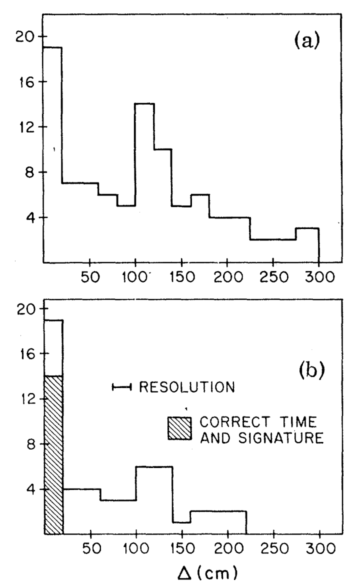

FIG. 2. (a) The distribution in the distance between the extrapolated muon tracks at the z position where an interaction occurred. (b) The distance between the extrapolated muon tracks after the muons were required (i) to have the correct timing, (ii) to have a track configuration with vertex inside the target, and (iii) to traverse the correct counter hodoscope units. The accepted events are cross hatched.

tance of closest approach was required to be inside the target; (ii) the muon trajectories obtained from the spark-chamber measurements were used to determine which of the segmented scintillation counters (B, C, and D in Fig. 1) were traversed by the muons. The time differences of the muons in separate counters were then required to be less than 20 nsec or, where appropriate, the pulse height in a single counter was required to be twice minimum ionizing. These requirements result in the distribution shown in Fig. 2(b). After both criteria are applied all events have Δ less than 20 cm, which is compatible with a common origin of both muons and the calculated resolution in Δ. These fourteen events constitute the accepted sample. The probability for an accidental time and space superposition of muons from independent neutrino and antineutrino interactions is estimated to be less than 5×10^{-6}, leading to a background contamination in the accepted sample of less than 0.1 event from this source.

The accepted events are distributed in muon sign as follows: 14 $\mu^+\mu^-$, 0 $\mu^-\mu^-$, and 0 $\mu^+\mu^+$. The distribution of the rejected events is 40 $\mu^+\mu^-$, 23 $\mu^-\mu^-$, and 25 $\mu^+\mu^+$. Eight events are produced in the liquid and six events in the iron. Figure 3(a) shows the scatter plot of the muon momenta for

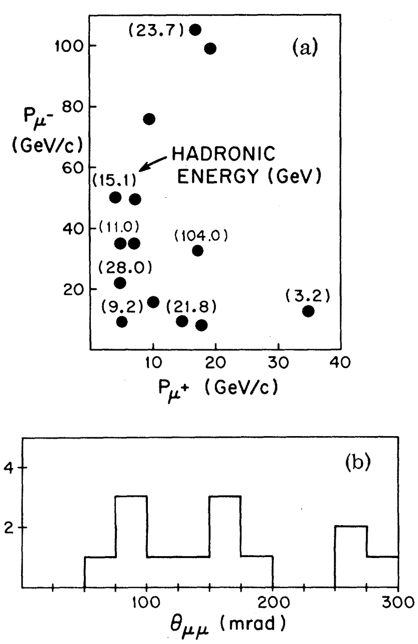

FIG. 3. (a) Scatter plot of the muon momenta for each event and the accompanying hadronic energy for calorimeter events. (b) Distribution in dimuon opening angle.

each event. The minimum visible energy for each event is calculated from the observed muon energies; for events in the calorimeter the hadronic energy is also available. The minimum energy of the events is distributed as follows: three in the interval 20–40 GeV, six between 40 and 60 GeV, two between 60 and 100 GeV and three above 100 GeV. The opening-angle distribution of the muons is shown in Fig. 3(b). Note that the average opening angle is approximately 150 mrad. Using the observed events, we estimate the detection efficiency to be 0.15, including the geometry of the apparatus, reconstruction efficiency, and the requirement that both tracks of an event pass through at least two spark chambers. The overall detection efficiency and thus the rates reported here are uncertain to within a factor of 2. The rate for $\mu^+\mu^-$ production is $(9\pm 3)\times 10^{-3}$ per single muon event for neutrino energies greater than 40 GeV, where the error is statistical only. The single-muon sample with energy greater than 40 GeV, corrected for detection efficiency and fiducial volume, contains approximately 3×10^3 antineutrino events and 5×10^3 neutrino events. The total single-muon sample contains 21×10^3 events.

No events with three muons in the final state have been observed. The estimated detection efficiency for trimuon events is approximately one half that for dimuon events.

We have examined the characteristics of the observed dimuon events against the possibility that they arise from a neutrino-induced single-muon event followed by the decay of a pion or kaon into a muon. We remark as follows.

(1) The masses of the liquid and iron targets, and the calculated detection efficiencies for dimuon events from them, are approximately the same, but the effective absorption lengths differ by a factor of about 4. Hence, if the six events from the iron target were all due to pion and kaon decays in flight, we should expect 24 events from the liquid target; we observe only eight events from the liquid.

(2) Another feature of the dimuon events is the preference for opposite-sign muons. If m is the number of π mesons of charge opposite to that of the muon produced in the initial inelastic neutrino or antineutrino interactions, and t is the total number of charged pions produced, the corresponding probability of obtaining dimuon events with opposite signs of the electric charge is m/t, which is expected to be in the range 0.5 to 0.7. Note again that the same ratio observed for the rejected candidates is 0.55. The binomial distri-

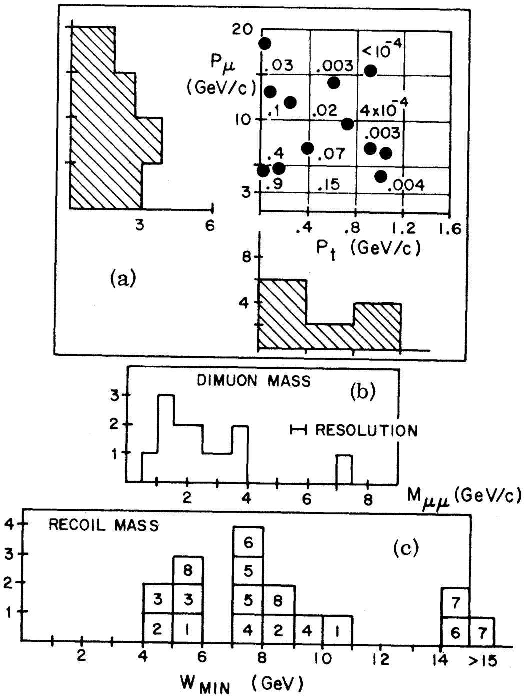

FIG. 4. (a) Scatter plot of the lowest value of the momentum component transverse to the neutrino-muon plane against the corresponding muon total momentum. The observed p_t-p_μ distribution is compared with the distribution expected from π and K production and decay in flight, which is given by the numerical values in the boxes. (b) Dimuon invariant mass distribution. (c) Distribution in the recoil mass $W_{\rm min}$. Two values are plotted for each event.

bution applied to the sample of fourteen dimuon events yields $(m/t)^{14}$ for the probability of observing zero events with the same signs of the electric charge.

(3) We define the transverse momentum p_t of a given muon with respect to the plane formed by the incident neutrino beam and the other muon. The plane must also contain the momentum vector of the recoiling hadronic jet, and therefore p_t is the projected transverse momentum with respect to the hadronic jet. If the muon arises from pion decay, p_t is very closely the projected transverse momentum of the pion, typically less than 300 MeV/c. Figure 4(a) shows a scatter plot of p_t against p_μ, the associated muon momentum. For each event there are two values of p_t since the primary muon is not identified, and we have chosen the smaller value. Figure 4(a) shows that the p_t distribution is roughly uniform up to ~1 GeV and inconsistent with the exponential falloff characteristic of multihadron production.

Using hadronic-jet characteristics obtained from electroproduction data[5,6] and scaling functions obtained from neutrino data,[4] we have calculated the distribution in the p_μ-p_t plane expected from pion decays in flight. Strange-particle production by neutrino or antineutrino beams is expected to be unimportant. The results of the calculation are shown in Fig. 4(a). Observe that (i) the calculated absolute number of events is much less than the observed number, and that (ii) the calculated distribution peaks sharply at small values of both p_t and p_μ, in contrast to the observed distribution. These results have been tested by direct measurements in which a pion beam of various energies (15 to 150 GeV) was incident on the calorimeter. Out of 3000 pion interactions no candidates with a secondary muon of energy greater than 5 GeV were observed and only two candidates with a muon energy between 2 and 5 GeV were recorded. We conclude that the dimuon events are very unlikely to arise from pion or kaon decay.

The distribution in invariant mass of the muon pairs $M_{\mu\mu}$ is shown in Fig. 4(b). It is essentially uniform in the interval 1 to 4 GeV. The dimuon mass resolution is calculated to be ±0.2 GeV.

For events in which the interaction occurs in the ionization calorimeter, the total energy of the hadron system E_H is determined. For such events the distribution in minimum invariant mass, $W_{\rm min}$, of the system recoiling against each of the outgoing muons is shown in Fig. 4(c). Here

$$W_{\rm min}=[2m(1-v_{\mu1})(E_H+E_{\mu2})+m^2-2mE_{\mu1}v_{\mu1}]^{1/2}, \qquad (1)$$

with m the mass of the nucleon and $v_{\mu1}=(E_{\mu1}/2m)\sin^2(\theta_{\mu1}/2)$. Equation (1) yields $W_{\rm min}$ because we have set equal to zero any missing energy —for example, from an outgoing neutrino or antineutrino—that would add to the energy sum in the first term. Since we do not know which is the primary muon, we have plotted two values for each event in Fig. 4(c). We note that the average value of the $W_{\rm min}$ is ~7 GeV for dimuon events compared to the mean value of the recoil mass observed from single-muon events of approximately 3 GeV, and that there are no dimuon events with $W_{\rm min}$ below 4 GeV.

A tentative conclusion concerning the origin of these events is obtained from the following points:

(a) The flat dimuon mass distribution is inconsistent with predominant production and decay of a narrow neutral vector boson. (b) The absence of trimuon final states and the predominance of events with opposite electric charge is indicative that the dimuon events have, by lepton conservation, an undetected neutral lepton. The calculated cross section for the coherent process $\nu + Z \rightarrow \nu\mu\mu Z$ is several orders of magnitude smaller than the dimuon signal, and the corresponding incoherent process has an even smaller cross section.[7]

Without the intervention of higher-order-weak or weak-electromagnetic interactions which are expected at a much lower rate, the only known mechanism that can produce trilepton final states accompanied by hadrons is the production and weak decay of one or more new particles. Such particles could be hadrons which carry a new quantum number[8] not conserved by the interaction responsible for the decay. From the characteristics of the dimuon events we may deduce that, if the particle is a hadron, the mass is greater than ~2 GeV [from the p_t distribution, Fig. 4(a)] and less than ~4 GeV [from the W_{min} distribution, Fig. 4(c)], and the lifetime is required to be less than 10^{-10} sec. We would like to call such particles y particles because of the probable relation of the dimuon signal to the violation of charge-symmetry invariance observed in the antineutrino y distribution.[2,4] An alternative explanation of the dimuon events is, however, through the production of a neutral heavy lepton, that decays into two muons and a neutrino or antineutrino. This is a less likely explanation, but it cannot be ruled out at present.

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Is the $\psi(3100)$ a $\Omega\bar{\Omega}$ Compound?

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It is proposed to connect the new narrow resonance with a *d*-wave bound state of the $\Omega\bar{\Omega}$ system where annihilation may be sufficiently suppressed by the centrifugal barrier. The width is estimated on the basis of a similar estimate for the φ and ρ. As an alternative, the possibility of relating the ψ and ψ' to a two-nucleon, two-antinucleon system is discussed.

The very small width of $\psi(3100)$ of about 60 keV[1] suggests that this state is a compound of (at least with regard to strong interactions) *stable* constituents with total mass >3100 MeV. For a bound state of two particles with equal mass, the mass of the constituents should be >1550 MeV. Among the *known* particles there are only the $\Omega^-(1672)$ and the atomic nuclei which fulfill this condition. Since $\psi(3100)$ is produced in e^+e^- collisions its baryon number has to be zero. If one assumes that the production occurs in lowest electromagnetic order (only one virtual photon) then it must have $J^P = 1^-$. I therefore like to conjecture the $\psi(3100)$ to be a 1^- compound of a sta-