Evidence for $\Delta S = -\Delta Q$ Currents or Charmed-Baryon Production by Neutrinos*

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We report on the production by neutrinos of an event with negative strangeness. In an exposure of the Brookhaven National Laboratory 7-ft cryogenic bubble chamber to a broad-band neutrino beam 335 events were observed, one of which fits the reaction $\nu p \to \mu^- \Lambda^0 \pi^+\pi^+\pi^+\pi^-$. Alternative explanations are examined and none found with a probability greater than 3×10^{-5}. The event thus represents a large violation of the $\Delta S = \Delta Q$ rule or alternatively the production and decay of a charmed baryon state. The most plausible mass for this state is found to be 2426 ± 12 MeV.

The recent discovery of high-mass (~3 GeV), narrow ($\Gamma \sim 100$ keV) boson states at Brookhaven National Laboratory and Stanford Linear Accelerator Center[1] has given rise to and revived a wide variety of theoretical speculations[2] concerning the nature of such phenomena as well as increasing experimental activity in the search for further such states. In this light we wish to report the existence of an event apparently initiated by a high-energy neutrino interacting in hydrogen producing a single strange particle, namely, a Λ^0. The most plausible interpretation of this event is

$$\nu p \to \mu^- \Lambda^0 \pi^+\pi^+\pi^+\pi^-, \tag{1}$$

which is a clear violation of the $\Delta S = \Delta Q$ rule, so well satisfied in low-energy weak interactions.[3] One is led to speculate that this indeed is the first example of the production of a "charmed" baryon.[2] In this case the most likely mass for the charmed baryon is 2.426 ± 0.012 GeV, a value consistent with that expected when extrapolating from the observed narrow boson state at 3.1 GeV.

The data come from an exposure of the Brookhaven National Laboratory 7-ft cryogenic bubble chamber to a broad-band neutrino beam with maximum flux near 2 GeV. The event reported here is one of 100 neutrino events obtained from an analysis of 62 000 pictures taken with the chamber filled with hydrogen. 68 000 pictures with a deuterium fill have also been analyzed, yielding an additional 235 neutrino events. Approximately 14% of all events have visible energies greater than 4 GeV and 1.5% have observed energies greater than 10 GeV.

The event is shown in Fig. 1; space limitations prevent inclusion of a table of track parameters.[4] The event is seen to have two negative tracks, three positive tracks, and a single V pointing to the vertex. The V is clearly a Λ^0 associated with the primary vertex; its mass is measured to be $M_\Lambda = 1116.9 \pm 3$ MeV. The alternative hypothesis of a $K_S^0 \to \pi^+\pi^-$ yields a mass 370 ± 7 MeV and is clearly ruled out. The two negative tracks (tracks 1 and 4) leave the chamber without interacting and are thus consistent with being either π^- or μ^-. None of the positive tracks can be a K^+. The first positive track (track 2) is observed to decay into a μ^+ which subsequently decays into a positron. On the second positive track (track 3), momentum 588 MeV/c, there is a δ ray measured to be 4.1 ± 0.4 MeV. The maximum energy of a δ ray on a kaon is 1.95 MeV, thus ruling out the kaon hypothesis. The third positive track (track 5), momentum 211 MeV/c, scatters elastically from a proton. Ionization strongly favors the pion interpretation but is not conclusive.[5] However, from a consideration of the overall kinematics of the event, this third positive track cannot be a K^+. This we now proceed to discuss in greater detail.

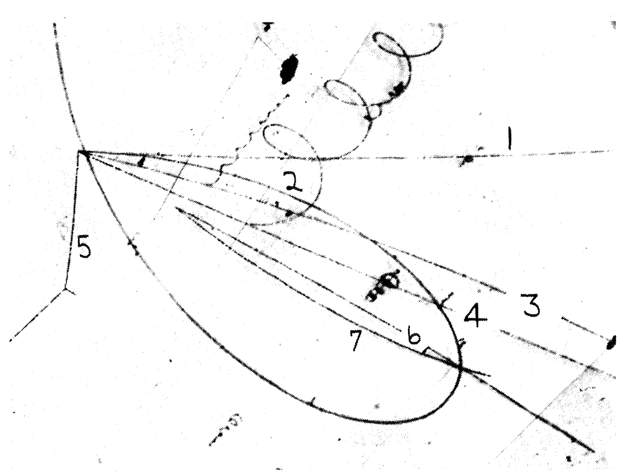

FIG. 1. View of event as seen in camera 3.

A lower limit on the mass of the incoming particle, M_{in}, can be calculated from a knowledge of the momenta and masses of all the visible particles:

$$M_{\text{in}}^2 = (E_{\text{tot}} - m_p)^2 - P_{\text{tot}}^2$$
$$\geqslant (E_{\text{vis}} - m_p)^2 - P_{\text{vis}}^2 = M_{\text{vis}}^2, \qquad (2)$$

where m_p is the proton mass, E_{tot} and P_{tot} are the summed energy and momenta of all outgoing tracks, and E_{vis} and P_{vis} are the summed energy and momenta of the visible outgoing tracks. The assumptions of Eq. (1) yield $M_{\text{in}}^2 \geqslant -0.17 \pm 0.20$ GeV^2 consistent with a value $M_{\text{in}} = 0$ expected for an incoming neutrino. This is to be contrasted with a value of $M_{\text{in}}^2 \geqslant +7.5 \pm 0.2$ GeV^2 if we assume that track 5 is a K^+, from which we conclude that track 5 is a π^+. Similar kinematic considerations applied to tracks 2 and 3 also eliminate their interpretation as K^+'s, thus corroborating the conclusion reached via the δ-ray analysis and observed decay. The possibility that any of the positive tracks are K^+'s that decay either at rest or in flight is also eliminated by these considerations.

We find not only that the incoming mass M_{vis}^2 is consistent with zero but that the vector sum of all visible track momenta is consistent with the neutrino beam direction ($0.47° \pm 0.6°$). There is thus no evidence of a missing outgoing neutral. If we assume an incident neutrino, and lepton conservation, then the above considerations identify the reaction to be that shown in Eq. (1), the only ambiguity being between the μ^- and π^- tracks. This hypothesis satisfies the three-constraint fit with 60% probability, the neutrino energy being 13.52 GeV.[6]

We will now discuss the background from alternative but improbable interpretations. The first is from associated production of strange particles by neutrinos, fewer than two of which would be expected with energy above 4 GeV. We first consider the possibility that two of the charged pions emerging from the primary vertex come from a decay of K^0 whose track length was too small to be observed. There are six possible $\pi^+\pi^-$ combinations, only one of which has a mass near to that of a K^0, tracks 1 and 3 with $M(\pi^+\pi^-) = 461 \pm 6$ MeV.[7] An extrapolation of these particular charged tracks (1 and 3) back to the vertex indicated that this intersection lies within 0.5 mm of the primary vertex. The probability for such a 1.8-GeV/c K^0 decaying in 0.5 mm is 5×10^{-3}; this coupled with the mass deviation yields a background of less than 10^{-6} from this hypothesis.

A second possibility is that the K^0 remained unobserved through either its K_L^0 component or the neutral decay mode of K_S^0. We note again that the calculated square of the mass of the incoming particle (M_{vis}^2) is consistent with zero. The presence of a missing particle must increase M_{vis}^2. Thus we find that a missing K^0, if it existed, would have to have high momentum (so as not to increase M_{vis}^2 too much) and be directed in a 2° forward cone (so as not to introduce an imbalance in the transverse momenta). If we allow a 2 or more standard deviation error in M_{vis}^2, then a K^0 with a momentum of 5.0 GeV/c or more is required. This, of course, increases the required incident neutrino energy to 18.5 GeV or more where the calculated neutrino event yield (flux times cross section) is a factor of 25 less than at 13.5 GeV. If the 9.8-GeV/c track is a muon and we assume the presence of a 5.0-GeV/c K^0 in the forward direction, then we find a transverse momentum of 705 MeV/c for this K^0, determined with respect to the computed mean hadron direction. It has been seen in both electroproduction and neutrino interactions that there is a characteristic exponential falloff of transverse momentum with respect to the mean hadron momentum direction, similar to that observed in strong interactions. Under the assumption of an $\exp(-4.4P_\perp^2)dP_\perp^2$ inclusive distribution of kaon transverse momenta,[8] then the calculated probability of having a K^0 with 705 MeV/c transverse momentum produced within a 2° cone is 1.5×10^{-2}. The further probability of the required error in M_{vis}^2, coupled with the flux reduction factor multiplied by the appropriate number (one) of associated events, yields an overall probability for this hypothesis of 3×10^{-5}. The calculation has been repeated for different values of K^0 momentum, and the integrated probability is found to agree with the above value. Similar considerations for the case in which the 1.2-GeV/c track is the muon and the 9.8-GeV/c track is the pion yield a probability of 2×10^{-4}. But this is reduced to a negligible value by the abnormal longitudinal and transverse momentum of the 9.8-GeV/c pion.

Two other alternative explanations of this event involve invoking different neutral particles initiating the reaction, namely an antineutrino or a K_L^0 which we now discuss. The antineutrino contamination in this horn-focused beam is 1%, which, taken together with the known ratio, $\frac{1}{3}$, of antineutrino to neutrino cross sections, would predict a total of one antineutrino-induced event. The distribution of such events in the variable $y = 1 - E_\mu/E_\nu$ is expected and observed[9] to vary like $\epsilon + (1-\epsilon)(1-y)^2$ with a value for ϵ on the order of 10%. If this event is indeed induced by an antineutrino, then track 3 is the only μ^+ candidate and the value of y is 0.956. The probability of a value of y so near to 1.0 is then only 1.3%. However, single-strange-particle production, which is allowed and observed at CERN, proceeds at a rate of only 4%.[10] In addition, the likelihood of this interpretation is further reduced by the presence of track 4 which must be identified as a pion with transverse momentum 1.20 GeV/c; the probability for one of four tracks having this much or more transverse momentum is less than 1%. The combined probability for this interpretation is thus 0.5×10^{-7}, clearly negligible.

We will now discuss initiation by K_L^0's. A K_L^0 must be produced by neutrinos in the last interaction mean free path of material in front of the chamber, in this case the magnet coil. The expected number of events in which a neutrino interacts in the copper coil and the emerging K^0 interacts in the bubble chamber is four, consistent with three such possible candidates observed. To simulate the observed event the neutrino energy has to be greater than 13.5 GeV (1×10^{-2}); the emerging K^0 must have an energy of 13.5 GeV and emerge from the neutrino interaction within 0.6° of the neutrino direction (5×10^{-3}), yielding 2×10^{-4} event. However, this is reduced to a negligible value by the abnormal longitudinal (72% of E_ν; 1% probability) and transverse momentum (1.24 GeV/c; 0.6% probability) of track 4.

We conclude that the most likely alternative explanation is that of strange-particle associated production with a missing K_L^0 in the forward direction, with a probability $\simeq 3\times10^{-5}$. All other explanations, and there are many that have been considered,[11] have calculated probabilities of 10^{-6} or less.

It is clearly difficult to establish unambiguously a new effect with one event since alternative hypotheses, although improbable, still have a finite probability. However, ignoring *a priori* prejudices, the most straightforward interpretation of this event is that of single-strange-particle production by neutrinos. Since the hadron charge changes from +1 to +2 and the strangeness from 0 to −1 in going from the initial to final hadron system, the simplest interpretation of the event is that of apparent $\Delta S = \Delta Q$ violation in semileptonic interactions at high energies. However, the rate of production (one in forty events above 4 GeV) implies a strength of $\Delta S = -\Delta Q$ comparable in magnitude to $\Delta S = +\Delta Q$, in striking variance to the limits of a few percent in amplitude[3] measured at low q^2. This rate argument as well as the hadronic effective masses suggests charmed-baryon production.

For the purposes of deriving masses, we assign the 9.75-GeV/c particle as the μ^-. To do otherwise implies the production of a pion of unreasonably large longitudinal and transverse momenta. Given this assignment we obtain for the total recoiling hadron mass ($\Lambda\pi^+\pi^+\pi^+\pi^-$) 2426 ± 12 MeV.[12]

This mass is in reasonable agreement with the values predicted by De Rújula, Georgi, and Glashow[13] for the lowest-lying charmed-baryon states of charge +2, 2420 MeV ($J^P = \frac{3}{2}^+$, $I=1$, Σ_C^*) or 2360 MeV ($J^P=\frac{1}{2}^+$, $I=1$, Σ_C), if one takes into account the uncertainty of 50–100 MeV in the prediction of absolute mass values. Of equal significance is the expected decay mass, the dominant mode for both the above states being via π^+ emission to a baryon of charge +1 with mass 2200 MeV ($J^P=\frac{1}{2}^+$, $I=0$, Λ_C). This yields a mass difference of 220 MeV for the former ($\Sigma_C^* - \Lambda_C$) and 160 MeV in the latter instance ($\Sigma_C - \Lambda_C$). There are three π^+'s and thus three possible mass differences derivable from this event; these are observed to be 166 ± 15 MeV, 338 ± 12 MeV, and 327 ± 12 MeV. The first of these differences is in remarkable agreement with the 160 MeV predicted for the decay of a spin-$\frac{1}{2}$ charmed baryon Σ_C decaying into a charmed Λ_C.

We conclude then by noting that the signature ($\Delta S = -\Delta Q$), rate, and decay-mass pattern are consistent with charmed-baryon production. All dynamical variables are normal under this hypothesis. In contrast other explanations involve extreme fluctuations and thus represent small probabilities, 3×10^{-5} or less. With the obvious caveat associated with one event, we find this observation to be strongly indicative of charmed-baryon production.

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[1]J. J. Aubert *et al.*, Phys. Rev. Lett. 33, 1404 (1974); J.-E. Augustin *et al.*, Phys. Rev. Lett. 33, 1406 (1974); C. Bacci *et al.*, Phys. Rev. Lett. 33, 1408 (1974); G. S.

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[3]No evidence for $\Delta S = -\Delta Q$ reactions has been observed; the limits on the amplitude for such reactions are a few percent of the $\Delta S = +\Delta Q$ amplitudes at low q^2. See J. W. Cronin, in *Proceedings of the Fourteenth International Conference on High Energy Physics, Vienna, Austria, 1968,* edited by J. Prentki and J. Steinberger (CERN Scientific Information Service, Geneva, Switzerland, 1968), p. 289; K. Kleinknecht, in *Proceedings of the Seventeenth International Conference on High Energy Physics, London, England, 1974,* edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975), p. III-32.

[4]Values quoted are obtained from the means of thirty measurements. Errors are dominated by Coulomb scattering for all tracks except track 4. Systematic effects were checked by measurements of cosmic rays with the field off and by observing the stretch functions of 100 three-constraint fits to $\nu p \rightarrow \mu^- p \pi^+$. The magnetic field was checked by the range and curvature of track 2.

[5]The predicted ionization for track 5 is 3.4 times minimum for a π^+ interpretation and 13.1 times minimum for a K^+. The clear presence of gaps makes the K^+ interpretation very unlikely.

[6]Such an energy value is not exceptional in that there are four other events whose neutrino energy is greater than 13.5 GeV, consistent with that expected from a linear rising neutrino cross section and the known neutrino flux.

[7]The other $\pi^+\pi^-$ mass values are 425 ± 5 MeV, 734 ± 13 MeV, 721 ± 13, 1187 ± 13 MeV, and 1912 ± 37 MeV.

[8]The transverse-momentum distribution used here was taken from the fit to the observed electroproduction distribution in $p_\perp$ of pions [F. Brasse, in *Proceedings of the Sixth International Symposium on Electron and Photon Interactions, Bonn, Germany, 1974,* edited by H. Rollnik and W. Pfeil (North-Holland, Amsterdam, 1974), p. 263]. It is consistent with the distribution of pions observed in this experiment and gives a mean $p_\perp$ of 420 MeV/c which is close to the values of 350 and 450 MeV/c obtained for pions and kaons in strong interactions [G. Giacomelli, in *Proceedings of the Sixteenth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, 1972,* edited by J. D. Jackson and A. Roberts (National Accelerator Laboratory, Batavia, Ill., 1973), Vol. 3, p. 250]. The probability calculated here is insensitive to the exact form of this distribution.

[9]The distribution in y follows from simple parton theory where ϵ is the fraction of antipartons in the nucleus: $\epsilon = 0.06 \pm 0.06$, obtained directly from the y distribution observed in Gargamelle; $\epsilon = 0.05 \pm 0.02$, obtained from the ratio of ν to $\bar{\nu}$ total cross sections, again as reported by the Gargamelle Group [in *Proceedings of the Seventeenth International Conference on High Energy Physics, London, England, 1974,* edited by J. R. Smith (Rutherford High Energy Laboratory, Didcot, Berkshire, England, 1975), p. IV-95.

[10]D. H. Perkins, in *Proceedings of the Sixteenth International Conference on High Energy Physics, The University of Chicago and National Accelerator Laboratory, 1972,* edited by J. D. Jackson and A. Roberts (National Accelerator Laboratory, Batavia, Ill., 1973), Vol. 4, p. 224.

[11]For instance: associated production by neutrons, associated production by neutrinos on a deuterium nucleus, associated production of a Λ and K^0 in which the K^0 decays within 1 mm to $\pi^+\pi^-\gamma$ or $\pi^-\mu^+\nu$, production of a K^0 which decays into $\pi^+\pi^-\gamma$, $\pi^-\mu^+\nu$, or $\mu^-\pi^+\nu$ in each case mimicking a Λ, and production of a neutron that interacts such as to mimic a Λ.

[12]If the 1.21-GeV/c track is taken to be the μ^- this mass becomes 4604 ± 54 MeV.

[13]De Rújula, Georgi, and Glashow, Ref. 2.

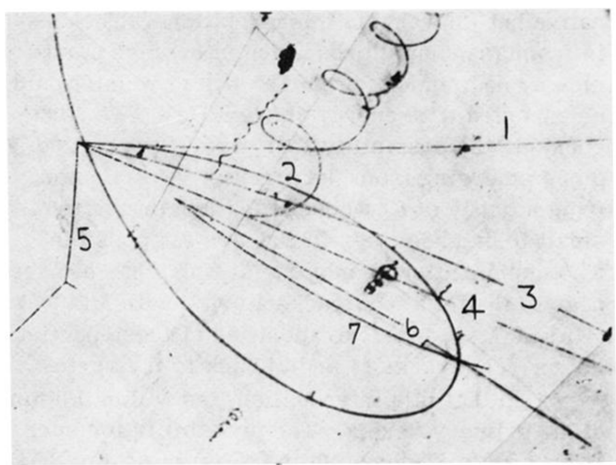

FIG. 1. View of event as seen in camera 3.