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HIGH-ENERGY NEUTRINOS IN THE UTAH APPARATUS*

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In about 5000 m^2 sr days, 2 neutrino events have been observed in the Utah detector. Redundant information obtained concerning the muons involved indicates that, with a very high probability, both were moving upward. The rate is consistent with other underground experiments, but one of the muons has the surprisingly high energy of more than 45 GeV and probably more than. 100 GeV.

The Utah underground cosmic ray detector is located at a depth of 1800 hg/cm^2 in the rugged Wasatch Mountain range. At this depth there is a flux of several hundred thousand atmospheric muons per year. .In order to identify a neutrino interaction, one of two criteria is used: (1) a muon passes upward through the detector; (2) the muon track begins in the apparatus. Because failures of one type or another can occasionally cause a normal atmospheric muon to simulate a neutrino event, an additional constraint is imposed: the probability of an atmospheric muon simulating the event must be less than 10% of the probability that a neutrino can cause the event.

The apparatus [1- 3] consists of four 1m x 6m x 10m water-filled Èerenkov counters flanked by 15 columns of triggered cylindrical spark counters (CSC's). Opposite walls of each Èerenkov counter are instrumented separately with vertical light collecting columns and photomultiplier tubes. A "wall pulse" is produced when pulses above threshold produce a coincidence between the odd-numbered columns and the even-numbered columns in a given wall. The CSC's are triggered when a coincidence occurs between wall pulses of two left-hand walls or of two right-hand walls. The path is determined by sparks in the CSC's which provide a resolution of 15 cm in a direction normal to the CSC axis and better than 1 cm in the direction parallel to the CSC axis. The sense of travel along the particle trajectory is determined by the combination of wall pulses occurring and by the time-of-flight measurement.

The apparatus was put into operation with an improved fast-timing system early in 1969. The first neutrino event occurred on 14 February 1969 (Fig. la). The muon started in the third Èerenkov tank and was inelastic, as evidenced by the additional discharge in CSC columns 7, 8, and 9. Wall pulses occurred in the left walls of the counters *B* and C, but not in the right walls, indicating upward motion-toward the left. Èerenkov light was collected in both left walls. No light was collected in the right wall of counter *B.* Èerenkov light was collected in the right wall of counter C,

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though it did not make a wall pulse (no odd-even coincidence); this light is probably associated with particles other than the muon produced in the inelastic reaction. The fast timing confirms the leftward travel of the muon; the time-of-flight measurement indicates that the wall pulse of counter B occurred 14 nsec after the wall pulse of counter C. The actual time-of-flight at the speed of light is 11.2 nsec. The difference is well within the tolerance of the fast timing system. There is a negligible chance that the event is due to an atmospheric muon with the opposite sense of travel mimicking a neutrino event. The slant depth to the surface along the muon path is greater than 15000 hg/cm^2. Furthermore, there is no direction within 5° of the path with a slant depth of less than 11000 hg/cm^2. The flux of muons from the appropriate direction even with extensive scattering is then not greater than an order of magnitude

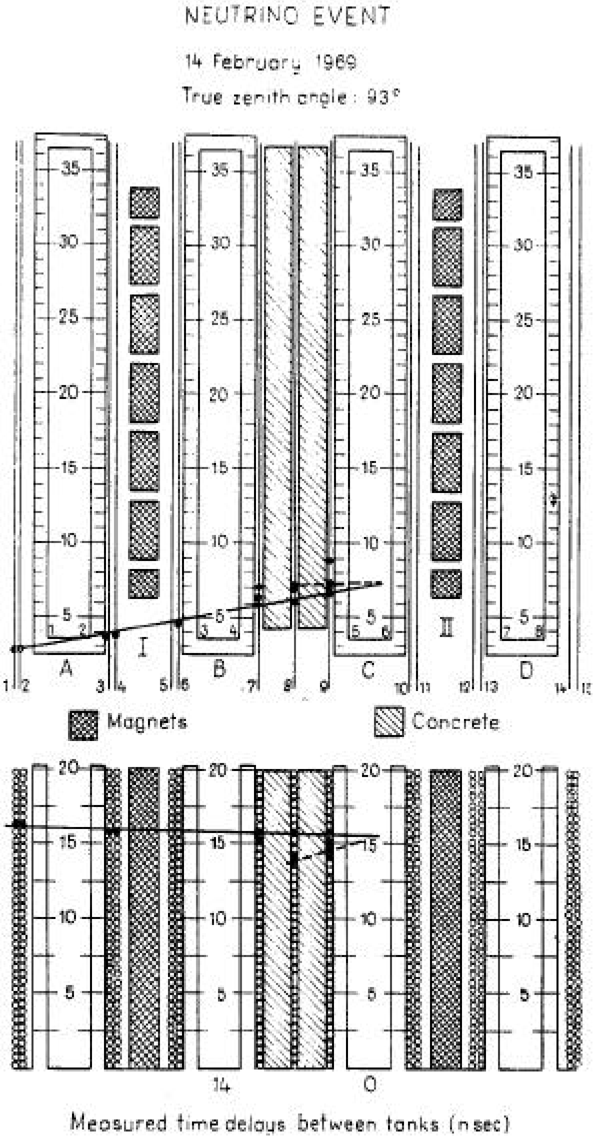

Fig. 1a

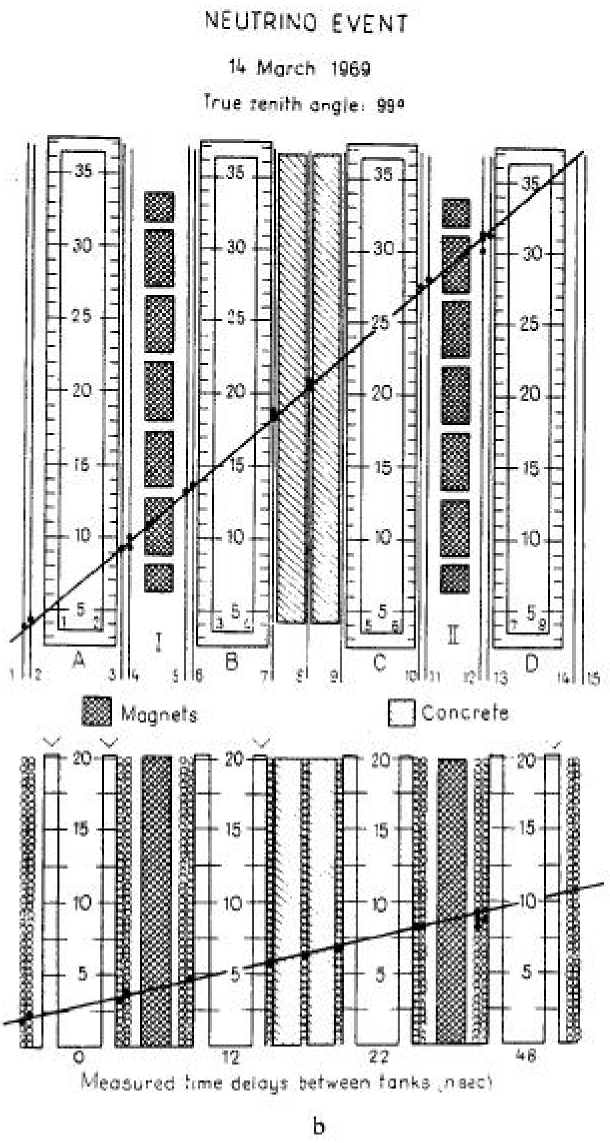

Fig. 1. Front and top views of the two neutrino events. A, B, C, and D are water-filled Èerenkov counters. Magnets and extra concrete are indicated. The columns of small round circles in the front view are the ends of the cylindrical spark counters (CSC's). CSC's which discharged are blackened in the front view and round black circles indicate the spark positions in the top view. (a) Neutrino event of 14 February 1969. An inelastic interaction occurred in Èerenkov counter C. The resulting soft shower is indicated by the dashed line and the muon path by the solid line. The zenith angle is 93°. Celestial coordinates are RA = $10^h\ 17^m$, ä = 12°. (b) Neutrino event of 14 March 1969. The V above Èerenkov counter walls indicates that wall pulses occurred in instrumentation on that wall. The zenith angle is 99°. Celestial coordinates are RA =

$15^h\ 45^m$, ä = 19°

more than the expected neutrino-induced muon flux in the opposite direction. The probability that such a muon could stop in the apparatus and give incorrect indications in the wall pulses and fast timing is many orders of magnitude smaller than the probability that a neutrino could produce such an event.

The muon passed through 3.85 cm Fe, 371 cm concrete and 92.7 cm H_2O. This yields a lower limit to the energy of 1.8 GeV. The muon did not pass through a magnet, so an accurate energy determination has not been possible. An analysis of scattering indicates that the energy probably lies between 4 GeV and 10 GeV.

The celestial coordinates for the event are: right ascension 10h 17m; declination 12°.

The second neutrino event occurred on 14 March 1969 (Fig. lb). This muon traversed the entire apparatus, permitting an excellent fast timing measurement and a good energy determination. Wall pulses occurred in both walls of counter A, on only the right walls of counters B and *D*, and on neither wall of counter C. A measurable amount of Èerenkov light was received on all walls except the left-hand walls of counters C and D. Fast timing measurements gave delays in tanks A, B, C, and *D* of 0 nsec, 12 nsec, 22 nsec, and 48 nsec respectively. The actual time of flight between successive counters determined from the path length at the speed of light was 15 nsec.

For this event the flux of muons with the opposite sense of travel is considerably larger than that considered in the first neutrino event. The slant depth to the surface in that direction is 6370 hg. At a zenith angle of 81°, the atmospheric muon flux is approximately $10^{-9}/\text{cm}^2$ sec sr, about 4 orders of magnitude greater than the neutrino-induced muon flux. We ignore the wall pulses in counters A and C which give no directional information. At the appropriate angle to the normal (42.5°), the probability for failure of a forward wall pulse is 0.18. The probability of a rear wall pulse is 0.09. Thus the probability of an incorrect direction indication from two counters is 3×10^{-4}. The probability that the fast timing could fail in a way giving successively larger delays in the wrong direction with about the correct delays is difficult to determine. Incorrect directions with delay differences as large as were observed occur even less often. In particular, delay errors as large as 48 nsec have never been observed. The probability that two adjacent counters will indicate the direction incorrectly from fast timing measurements is 0.02. Unless there is some coherent effect which has eluded us, in this case the fast timing has less than one chance in 10^5 of indicating the direction incorrectly. Even if the probability of a fast timing error is as great as 10^{-2}, the muon is almost certainly moving upward and should be interpreted as a neutrino event.

Fig. 2 shows more detail regarding the trajectory of the particle, with the horizontal distance perpendicular to the CSC axes displayed on the abscissa and the distance along the CSC axes between the best fitted straight line and the sparks displayed on the ordinate. Note that the ordinate is expanded by a factor of 100. The line is fitted to all sparks except those to the right of magnet II. A small shower coming out of that magnet produced a large number of sparks making it difficult to identify those associated with the muon. Knowledge of the muon path to the right of magnet II would add little to the momentum determination.

Two effects can obscure a path determination. The first involves knock-on electrons. If a knock-on goes through a CSC on the same side of the muon path as the microphone, the muon-induced discharge may not be recorded. The result on a graph like Fig. 2 would be to produce points which are too low. A knock-on electron on the other side of the muon path will have little effect.

The second effect occurs for oblique muons if the muon path passes very near the centre wire of the CSC. In this case most of the ions in the centre part of the path through the CSC will be collected at the clearing potential. When the additional potential needed to produce a spark is applied, each end of the ion trail will produce a spark. Then the correct position is half-way between the two sparks. In Fig. 2, sparks 4 and 5, sparks 8 and 9, and sparks 10 and 11 may form such pairs. The x indicates the correct position if this is correct. This interpretation is highly likely to be correct for the latter two pairs.

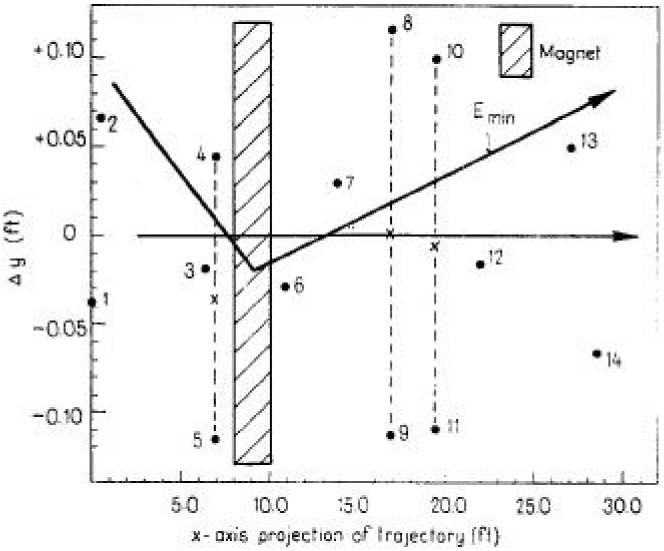

Fig. 2. Positions of sparks in 14 March 1969 event relative to the best fit straight line to all sparks left of magnet II. The vertical scale is expanded by a factor of 100. Sparks connected by a vertical dashed line were treated as single sparks at the position marked x. The solid line labeled E_{min} is the lowest energy fit considered reasonable. It is obtained by ignoring sparks 1, 5, 12, and 14; it yields an energy of 45 GeV

If it is assumed that there are no knock-on electrons and that the x's represent the best measurement of the muon path, then the best fit to a muon path with two straight-line segments joining in the centre of the magnet yields an energy greater than 100 GeV with a slight preference for a negative charge.

The lowest energy one can assign comes from assuming that sparks 1, 5, 12, and 14 are due to knock-on electron. Then the bent path of Fig. 2 is indicated. The energy for such a path is about 45 GeV with a negative charge.

This muon has right ascension 15^h 17^m and declination + 19°.

The aperture for neutrino detection, when detection efficiency and suitable criteria for direction determination are allowed for is 47 m^2 sr. (It is anticipated that improvements being made in the Cerenkov counters will increase this significantly.) The running time is about 0.9×10^7 seconds. Both numbers are crude, being different for different energy muons. With two neutrino events, this indicates a flux of neutrino induced muons of about $5 \times 10^{-13}/cm^2$ sec sr. This number is probably within a factor of 3 of the correct flux and is thus consistent with the KGF and Case-WitsIrvine results, of a few times $10^{-13}/cm^2$ see sr.

If the neutrino cross-section rises linearly with laboratory energy, one would expect about equal numbers of muons in each decade of energy. The event of 14 March 1969 may be considered weak evidence that the rise continues well beyond 10 GeV.

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