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ULTRA-HIGH-ENERGY INELASTIC NEUTRINO-NUCLEON SCATTERING IN DUMAND*

A. Roberts

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by
Arthur Roberts

Fermi National Accelerator Laboratory, Batavia, IL 60510, U.S.A.

Abstract. We discuss in detail the problems involved in designing an experiment using cosmic-ray neutrinos to measure the y-distribution in neutrino scattering at 2-50 TeV, which should be capable of demonstrating the existence of the W through its propagator effect on the y-distribution.

Introduction. The inelastic scattering of neutrinos by nucleons ($\nu_\mu + N \rightarrow \mu + N'$) has been extensively discussed (1-4), taking into account the finite mass of the intermediate vector boson W±. The boson mass enters in the propagator, so that the expression for the differential cross-section may be written (3):

$$\frac{d^2\sigma}{dxdy} = \frac{G^2 M_W^{\,2}}{4M_p E_\nu} \; \frac{q(x) + \bar{q}(x)\;(1-y)^2}{(yx + M_W^{\,2}/\;2M_p E_\nu)^2} \qquad (1)$$

At accelerator energies, the second term in the denominator parenthesis outweighs the first, and the expression simplifies to a simple proportionality to E_ν. But when the c.m. energy approaches the W mass - a few TeV -the predicted distribution, instead of being flat, becomes sharply peaked at low y values (see Fig. 1, from Ref. 4).

In practice, the measurement of the y-distribution in DUMAND requires the measurement of the fraction of the neutrino energy imparted to the hadronic cascade - i.e. the inelasticity of the collision. At high energies the dominance of low y-values corresponds to the increasing elasticity of the collision - i.e. the transfer of most of the energy of the neutrino to the muon.

The possibility of making measurements of the y-distribution in DUMAND has been discussed for a considerable time, and this paper summarizes the state of the problem. For such a measurement to be feasible, we need, in addition to freedom from ambiguity in the theoretical interpretation of the data,

(a) an adequate rate of observation of events;

(b) ability to distinguish true events from background;

(c) ability to distinguish the interaction products, muon and hadronic cascade; and

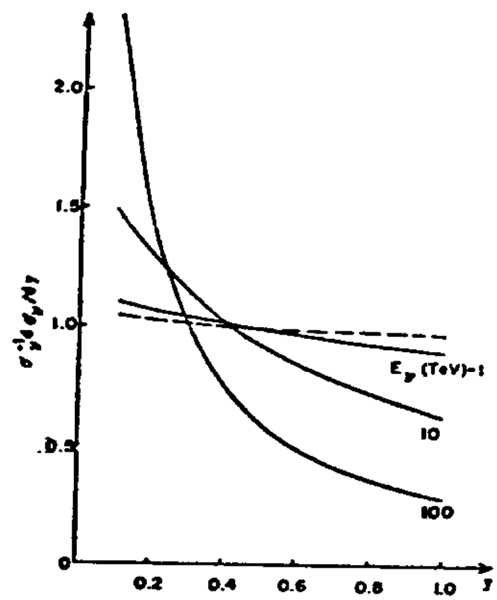

Fig.1. The y-distribution for a pure neutrino beam with the Wang quark distribution. The solid curves are for a boson mass of 80 Gev. the dashed curve for an infinite mass.

(d) the capability of measuring, with known accuracy, the energies of both the muon and the hadronic cascade.

The satisfaction of requirement (a) is demonstrated in Table I, from Ref. 7, which indicates that a year's data are adequate for a highly significant result.

TABLE 1. Expected Precision of Y Determination. Statistics and errors of measurement of the y-distributions expected in one year of operation of DUMAND (1 km^3). Event numbers quoted are from the integral spectrum - i.e. all events of energy E_ν and above. The difference between total and measured events includes estimated corrections for fiducial volume, unmeasurable events for various reasons, etc.

E_ν	No. of Events per year		Expected R =	Systematic Error if $\bar{\nu}$ Admixture	Total	No. of Std. Deviations
TeV	Total	Meas.	y>0.5/y<0.5	= 0.15±.075	Error	from R=1
4	3600	2000	0.720±0.03	±0.04	±0.05	6
10	700	400	0.630±0.06	±0.04	±0.07	6

The ratio R of the upper half to the lower half of the y-distribution is not the optimum method for demonstrating the change of shape; a fit to the distribution would make optimum use of the data.

Requirement (b) has been studied at some length; DUMAND must provide the equivalent of a highly efficient anticoincidence counter over its surface, so that muons entering the array from outside that produce a large energy loss in an inelastic collision are not confused with neutrino events arising from neutral primaries. That this can be done is not in question; but extensive Monte Carlo calculations will be needed to find what sensor spacing is needed, and what the fiducial volume requirements will be.

Requirement (c) poses no great difficulty until the hadronic cascade energy reaches values at which the emission of one or more muons from the cascade (from meson decay within it) becomes probable. According to Jones (14) the energy at which the probable number is one is about 100 TeV; and in addition the energy of such muons is expected to be much lower than that produced in the charged-current interaction. These events would appear to have large y-values, and a cutoff in y to remove neutral-current interactions is necessary in any case. Further Monte Carlo work is needed here.

Most of our work has been concerned with requirement (d), without which the other problems are irrelevant. Extensive Monte Carlo calculations have already been carried out (6-9). For concreteness, a fixed standard array configuration, which can eventually be optimized, has been used; it is the 1978 Standard Array (10).

Measurement of Muon Energies in DUMAND. - This is possible because at sufficiently high energies - ca. 2 TeV in water - the radiative energy losses of muons dominate, and as a consequence the rate of energy loss becomes proportional to muon energy, just as it is for electrons above the critical energy (e.g. 8 MeV in lead). The problem of energy measurement thus becomes the problem of measuring the rate of energy loss. This problem has been treated, e.g., by Borog et al. (11), and we have carried out extensive Monte Carlo calculations (6) to estimate the fluctuations to be expected, the length of path required for a good measurement, and the limitations on accuracy due to the unavoidable statistical fluctuations in rate of energy loss.

Thus, our procedure for muons has been:

1. Divide the trajectory into segments 100 meters long.
2. Using the analytical energy-loss expressions of Adair and Kasha (12), calculate the energy loss in each 100m segment, by Monte Carlo methods.
3. Find a suitable algorithm for estimating the muon energy from the observed distribution of energy losses.
4. Determine the accuracy with which such a procedure can find the muon energy as a function of muon energy, path length, etc.

The results of such calculations have been given by Roberts (6). They serve as the starting-point for the next stage of the calculations (8), which is to simulate the array by a set of sensors of assumed sensitivity (the 1978 Standard Array (10) is the starting-point),and by passing muons through the array at random angles. determine the capabilities of a given array for measuring the energy and direction of each muon. The energy alone is required for the y-distribution; but a measurement of muon direction is crucial to the use of DUMAND for observing extraterrestrial neutrinos, since good angular resolution allows point sources to be distinguished from a diffuse background.

The results to date of this work are being reported elsewhere in this session (8) and are encouraging. Even the 40-meter spacing assumed in the 1978 Standard Array is adequate for muon energies at a few TeV and above, and the accuracy is adequate for the purposes of determining the y-distribution.

Measurement of Hadronic Cascade Energy. - For the estimation of hadronic cascade energies, we have to date relied on the fact that hadronic cascades are not very different from electromagnetic ones, especially at very high energies. Recent Monte Carlo calculations by Jones bear out these assumptions (15).

Monte Carlo calculations on hadronic cascades are now being undertaken by Stenger et al. (8) and by T. Miyachi (9). Detailed results are not yet available. However, since the source functions for light from electromagnetic showers have been determined (17,18), and the propagation functions of the light in seawater are likewise known (19), the calculations should pose no difficulties, and preliminary results seem to verify this.

Fig. 4 shows the polar diagram of the light to be expected from a 1- and a 10-TeV cascade. What is needed in addition is the Monte Carlo study of the reconstruction of the cascade energy and orientation from the signals received by the sensor array.

Treatment of Systematic Errors in the Measurement of the y-Distribution. - The measurement of the y-distribution involves more than just measuring the muon and hadron energies. The cosmic-ray neutrino spectrum has an integral spectrum shape of the form $E^{-\gamma}$, where γ is variously estimated as lying between 2.5 and 2.8 in the energy range of interest (2-50 TeV). This steeply falling spectrum can introduce a bias into the results (14); this is because errors of opposite sign in the energy have different consequences. If the neutrino energy is estimated too high, it is introduced into a much smaller population than if the energy is too low. This will produce difficulties only if the effect of the incorrect estimation on y is different in the two cases; and it turns out that it is. It depends also on whether the error is in the hadron or the muon energy. These points have now been throughly explored by Monte Carlo calculations (7),

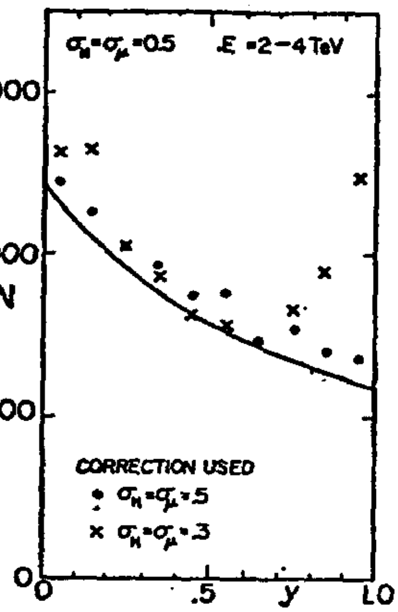

Fig. 2. The effect of correcting the errors described in the text. The full line is the true distribution; circles show data for errors of 50% in both hadron and muon energy, but corrected accordingly. Crosses show the effect of incorrectly estimating measurement error; the error is corrected as if it were .3 instead of .5

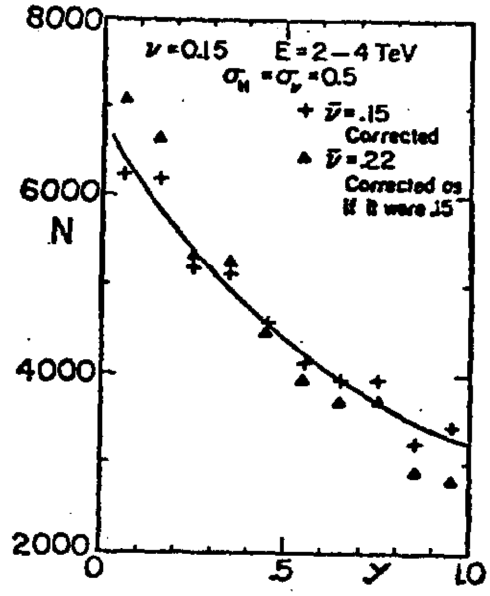

Fig. 3. This figure is similar to Fig. 2, but shows a distribution containing 15% antineutrinos. Crosses show values corrected using true antineutrino fraction, triangles the effect of incorrectly estimating the fraction as 0.15 when it was in fact 0.22 (a 50% error.)

which have also covered the question as to how the failure to distinguish neutrinos from antineutrinos should be corrected for, since antineutrinos show a a peaked $((1 - y)^2)$ distribution, even at low energies.

The calculations indicate that both of these effects can be properly corrected for (see Figs. 2 and 3), providing:

1. The neutrino energy spectrum is known. The range of γ noted above is small enough for this to be true.

2. The accuracy with which the hadron and muon energies are measured is also known. This is the resolution function necessary for deconvolution of the data. In laboratory experiments the resolution function is frequently determined by introducing a line spectrum and observing the apparatus response. In DUMAND an artificial source appears to be impractical; but nature provides an alternative. We expect about half the cosmic-ray muons to stop within the array. Then their energy at each point on their trajectory can be found, and thus we have a calibration point for minimum-ionizing muons with plenty of data. This will yield the desired resolution function.

3. The fraction of the total number of events due to antineutrinos is known; this will allow their contribution to the y-distribution to be removed.

The fraction of antineutrinos in the cosmic-ray neutrino spectrum is rather well known (16); and the cross-section for antineutrino interactions is also known at accelerator energies. The ratio of neutrinos to antineutrinos is just over 2, and the anti-neutrino cross-section is about one-third the neutrino cross-section, so that about one-sixth as many antineutrino interactions are expected as neutrino interactions. The Monte Carlo calculations (Fig. 3) show that even as large an error as 50% in such an estimate may be tolerable.

Conclusions. - We have omitted the effect on our calculations of such matters as scaling violations, and changes in the assumptions made concerning the quark structure functions q and $\bar{q}$ that appear in Eq. (1). These have been considered and found unimportant by Halprin (4) and by Halprin and Oakes (5). We conclude that there remain no difficulties in principle in carrying out the proposed measurements. The remaining problems are those of finding array parameters and experimental designs that are capable of making the required measurements with the postulated accuracy, at a reasonable cost. In view of progress to date, we remain optimistic.

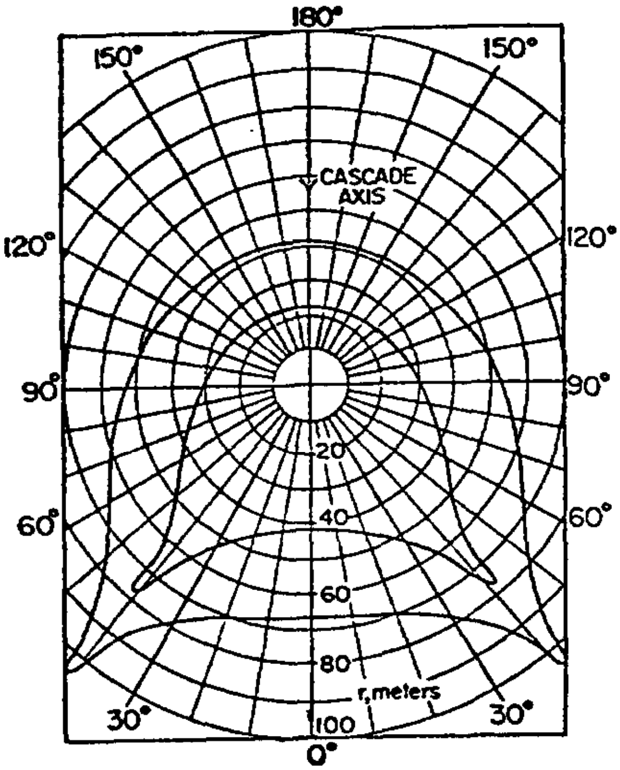

Fig. 4. Polar intensity diagrams of Cerenkov light from electromagnetic cascades of 1 and 10 TeV. The curves show equal-intensity contours for intensities of 200 quanta/m^2. Attenuation of light in the water has been taken into account, assuming 20m water, but scattering has not.

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