THE COSMIC RAY NEUTRINO-INDUCED MUON SPECTRUM AND THE INELASTIC NEUTRINO CROSS SECTION AT HIGH ENERGIES

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We report here the results of a measurement of the integral energy distribution of the neutrino-induced muon flux deep underground using the Utah neutrino detector. By comparing the observed and expected distributions we are able to set lower limits on the saturation energy E_0 of the total neutrino nucleon cross section or, equivalently, on the mass M_w of the intermediate vector boson if scale invariance of the inelastic structure function õW_2 is assumed. We find at the 1, 2, and 3 ó levels of confidence $M_w > 8.5, 4.5, 2.8$ GeV or $E_0 > 230, 165, 25$ GeV respectively.

1. Introduction. The observation of a muon flux induced by the interaction of cosmic ray neutrinos in rock deep underground has been used to investigate the nature of the weak interaction (Reines et al, 1971; Chen et al, 1971; Krishnaswamy et al, 1971; Hendricks et al, 1970). Previous experiments have yielded values for the integral muon flux but none thus far have analyzed the high energy spectrum of the observed muons. In this paper we report the results of a measurement of the spectrum of the underground neutrino-induced muon flux made possible by the unique Utah neutrino detector (Keuffel et al, 1967; Hilton et al, 1967; Bergeson et al, 1967; Cassiday et al, 1973). We compare the observed spectrum with those calculated for different assumptions concerning the high energy ($E_õ$ > 10 GeV) behavior of the neutrino-nucleon total cross section (Volkova, 1970 and 1973). Comments are made on the scale invariance of the structure functions measured in inelastic neutrino-nucleon scattering and a lower limit is placed on the mass of the intermediate vector (W) boson (Chen et al, 1971; Bjorken, 1969 and 1970).

2. Experiment. The Utah neutrino detector has been described previously in great detail (Keuffel et al, 1967; Hilton et al, 1967; Bergeson et al, 1967; Cassiday et al, 1973). Its three main detection elements are: (a) an array of 600 sonic ranging cylindrical spark counters used to determine the trajectory of each muon; (b) four water-filled Cherenkov tanks which provide the trigger for the detector as well as determine the directionality of the muon trajectory; (c) two 16-kilogauss iron magnets which determine the local energy of the muon (Ashley, to be published if less than 100 GeV. Because of the relatively shallow depth ($1.5 - 10^5$ g cm^{-2}) of the detector, the majority of the registered events are atmospheric muons passing through aperture with energies in excess of that required for triggering (2 GeV). Consequently, in order to avoid contamination of the neutrino -induced muon flux by the abundant atmospheric flux, rather stringent requirements are demanded of those muons which are to be classified as neutrino-induced. First, neutrino-induced muon candidates must satisfy the requirement of an upward going trajectory. The directionality of the trajectory is determined by the parity of the Cherenkov tank trigger (whether the right or the left hand walls of the Cherenkov tanks comprise the coincidence trigger) as well as a time

flight measurement between adjacent Cherenkov tanks. (The number of atmospheric muons during the course of this experiment which have scattered at large angles with residual energy sufficient to penetrate and trigger the thick Utah detector is negligibly small. Furthermore, the thickness and resolving power of the detector prohibit the detection of pions from photo-nuclear interactions as neutrino-induced muons.) The most probable source of contamination of the upward-going neutrino-induced muon flux is those downward going atmospheric muons which simulate upward-going ones as a result of an incorrectly determined directionality signature. The number of such muons is

$$M = t\, I\,(h,\ \theta)\, R(\theta, ö)\, A\,(\theta, ö)\, dÙ$$
$$AÙ$$

where t is the running time, A (θ, ö) dÙ is the differential detector aperture, I (h, θ) is the integral atmospheric muon intensity at depth h and zenith angle θ, and R (θ, ö) is the probability that a muon on a downward-going θ, ö trajectory produces an upward-going signature. R(θ, ö) is determined from the Cherenkov triggering efficiencies and the resolution of the time of flight electronics.

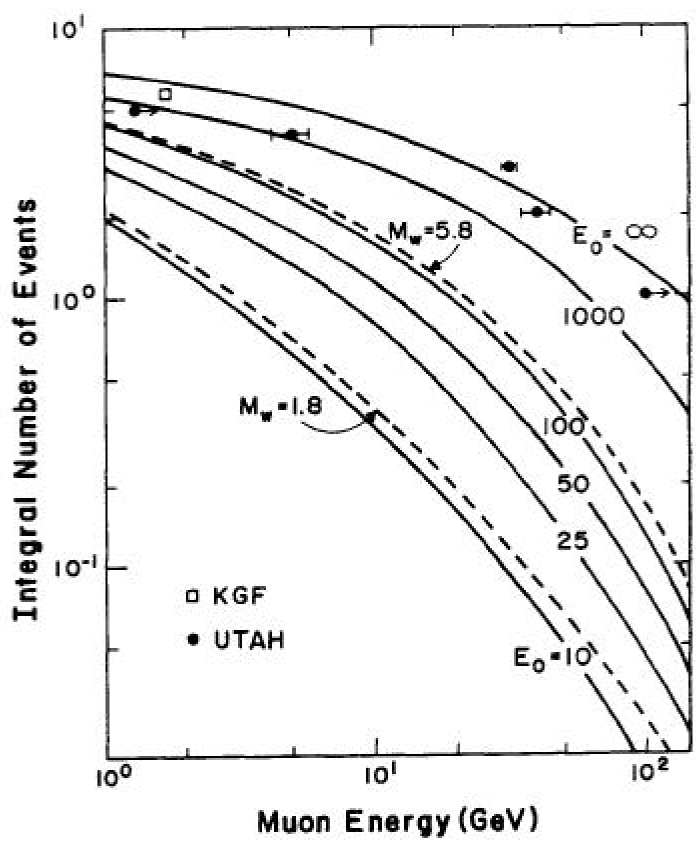
The total aperture (AÙ) for the experiment must be restricted to values small enough such that the above "contamination number" is small compared with the total number of neutrino-induced events, but not so small that neutrino-induced muon events are lost. (In particular, since I (h, θ) and R (h, θ) both increase dramatically as θ decreases, "cutting down" the aperture means restricting it more and more towards the horizontal.) Since we have only five neutrino-induced muon candidates, it is possible to satisfy the above condition with a rather broad range of values for AÙ. We estimate a value for the total aperture-running time of AÙt of = (2 .0 ± 0.6) . 10^{13} cm^2 sr sec. The lower limit (obtained by cutting down the aperture AÙ to the point where our first neutrino-induced muon candidate is lost) corresponds to the acceptance of 2 • 10^{-5} atmospheric muons, an exceedingly safe value which gives us confidence in the belief that all of our candidates are in fact neutrino-induced. The upper limit corresponds to an expected atmospheric muon contamination number of 0.3 which is where we see our first additional event (judiciously rejected as probably an atmospheric muon). The resultant integral distribution of the five neutrino-induced muon events as a function of muon energy is shown in Fig. 1. No statistical error bars are shown for reasons which we will discuss later.

<u>3. Analysis</u>. Two approaches have been used in analyzing the data. In each approach linear fits to the most recently available neutrino and anti-neutrino cross sections (Barish, private communication, 1973) from CERN for energies less than 10 GeV was used. Beyond this energy in the "simple" approach we assume that the cross sections continue to increase linearly with neutrino energy up to some saturation energy E_0 beyond which the cross sections remain constant. In addition, a constant energy transfer ratio (ª = < $E_ì$ / $E_õ$) 0.54 ± .06) taken from CERN measurements (Pattison, 1970) was used at all neutrino energies. The data is then used to place limits on the saturation energy. In the second approach, a W-boson "propagator" $1 + q^2/M_w^2$ is introduced into the neutrino-nucleon interaction which results in a logarithmic increase of the cross section with neutrino energy (Bjorken, 1970).

Furthermore, inclusion of the propagator results in an energy transfer ratio which approaches ~ 1.0 at high energy (H.H. Chen, et al, 1971). The precise behavior of each of these effects is governed by the mass of the boson. (For the moment we are considering only inverse-â-reactions. Modifications due to the possibilities of boson production will be considered later.) The second approach has, perhaps, the additional virtue of allowing us to set a more physically meaningful lower limit on the boson mass. We outline below the calculation of the expected integral number of neutrino-induced muon events as a function of muon energy. This number is

N (> $E_ì$) = t   Ö (> $E_ì$, θ) A (θ, ö) dÙ

where Ö is the integral nuetrino-induced flux, t is the running time and A(θ, ö) dÙ is the differential aperture for detecting neutrino-induced muons. This expression can be approximated by N (> $E_ì$) $Ö_h$ (> $E_ì$) AÙt where $Ö_h$ is the horizontal flux and AÙt is the aperture-running time as determined above. this approximation is permissible since our aperture is peaked toward the horizontal where the flux is also greatest. This conservative approximation results in an overestimate of the event rate of order 10%. The calculated horizontal flux is based upon the work of Volkova and Zatsepin (1970 and 1973) with the following qualifications: (a) The value of the K/π ratio used in obtaining the atmospheric neutrino flux is 0.1 (Liland et al, 1970). (b) In extrapolating neutrino-nucleon cross sections to our target (which is rock of Z   11, A   22) we take ó (õp) = ó (õn) and ó (ûp) = ó (ûn). Furthermore, we take the slopes ($ó_o$ and 00) of the low energy (< 10 GeV) neutrino and anti-neutrino total cross sections to be (0.69 ± 0.05) and (0.27 ± 0.02) * 10^{-38} cm^2 GeV^{-1} $nucleon^{-1}$ respectively (Barish, private communication, 1973). (c) In the "propagator" approach for neutrino energies above 10 GeV, logarithmically increasing total cross sections and increasing energy transfer ratios appropriate to inverse-â-reactions have been used.



Shown in Figure 1 are the experimental and calculated integral numbers of neutrino-induced muon events N (> $E_ì$) as a function of muon enenrgy. The KGF experimental results (based on 4 events in 1.4 * 10^{13} cm^2 sr sec) are normalized to our aperture-running time. In consideration for the alrnost vanishingly small statistics of the experiment we employ a direct probability argument in order to distinguish between the various distributions tributions of Figure 1. For each theoretical integral distribution of events as a function of muon energy, we calculate the probability of actually obtaining the observed integral distribution. This probability is the product of several factors: the probabilities of obtaining the given number of events for each independent experiment (based upon the Poisson distribution) and the probability that the obtained events have the indicated integral distribution (itself a product of probabilities based upon the weighted binomial distribution). Shown in Figure 2 are the resultant probabilities (normalized to the most probable distribution) as a function of M_w^{-1}. (In the case of the simple approach, we arbitrarily identify the cutoff energy E_0 with a boson mass M_w by the relation M_w^2 = 1/3 MpEO where Mp is the proton mass. The logarithmically increasing cross section parameterized by M_w in the propagator approach has a value equal to approximately 1/2 that obtained at E_0 with the unlimited linearly increasing cross section.) In addition, we show as dotted curves those probability limits obtained on the basis of estimates of known instrumental uncertainties. The uncertainties in question stem from a certain arbitrariness in our choice of aperture as well as the finite energy resolution (Ashley et al, to be published) of the detector. We obtain an upper probability limit by increasing the neutrino-induced muon aperture to its estimated upper value and by using the lower values for the measured muon energies. The lower probability limit is obtained by reducing the neutrino-induced muon aperture to its lowest estimated value and by using the upper values for the measured muon energies. These estimates, we feel, represent extreme limits in comparing the observed and calculated rates for each model. We note that applying these two limits to each model results in an overlap of the resultant probability curves.

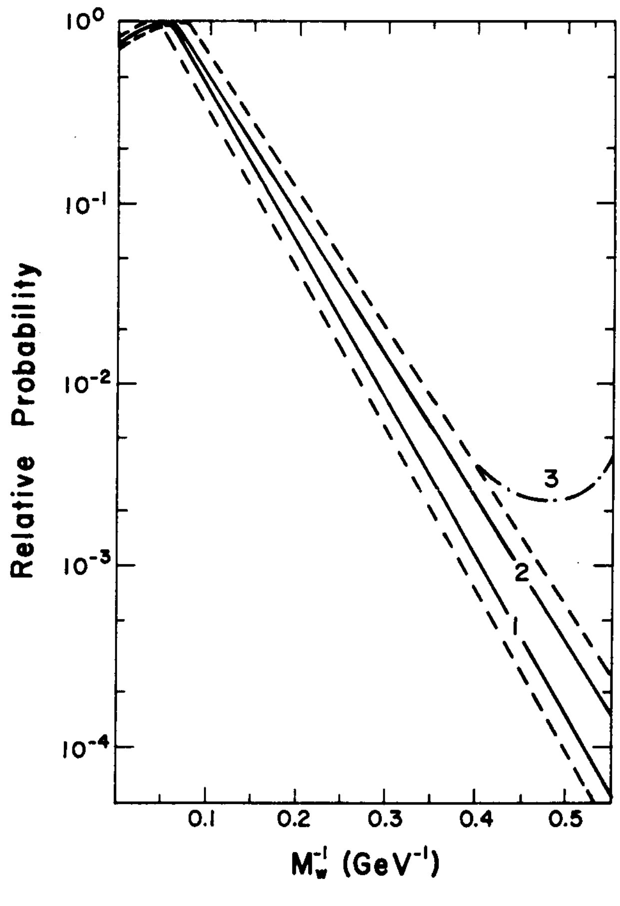


Figure 2.

4. <u>Discussion of Results</u>. Upon examining these relative probabilities of Figure 2, it can be seen that the data favor a cross section which saturates at E_0 > 3000 GeV (M_w > 30 GeV). However, at relative probabilities of 32%, 4.5°/ and .3% (which correspond to ó, 2ó, and 3ó) we obtain lower limits of M_w > 8.5, 4.5 and 2.8 GeV respectively (or equivalently, energy saturation values E_0 > 230, 65, and 25 GeV). We feel that these estimates represent an exceedingly conservative viewpoint for several reasons: (1) Throughout the analysis, when faced with a choice of parameters, we have taken conservative ones, (2) We have possibly overestimated our aperture by as much as 30% since we have not included the magnets in the aperture calculations (primarily due to geometrical difficulties),and (3) There are probably several low energy events in the vicinity of 1-2 GeV which we have lost due to detector bias. Thus, we tend to favor the

lower probability curves of Figure 2 which indicate an unlimited growth of cross section with increasing neutrino energy (E_0, M_w =).

We must point out that beyond 3.0ó our analysis above breaks down since we have ignored the possibility of W-boson production reactions. However, the contribution from this source to the neutrino-induced muon flux measured in this experiment is inconsequential for boson masses > 3 GeV. This is primarily due to the fact that bosons are not produced copiously unless their mass is small (H.H. Chen et al, 1971 and H.H. Chen, 1970) and the fractional energy transfer to the directly produced muons (Brown et al, 1971) for a given boson mass is typically smaller than that obtained in inverse-â-reactions at a given neutrino energy. Thus, although the high energy flux from boson production reactions is less significant than the corresponding flux from inverse- â -reactions (even for low mass bosons), this is not the case for the low energy flux. (It is precisely for this reason that we have failed to include in our analysis other deep mine integral flux measurements whose energy thresholds are less than 1 GeV). A crude estimate of the contribution to the flux from boson production leads to the probability distribution of curve 3 (to within a factor of 2) in Figure 2. Thus, all things considered, we can say nothing about limits on the boson mass (or saturation of the neutrino cross section) beyond the 3ó level.

Throughout the analysis we have tacitly assumed scale invariance of the inelastic structure function vW_2. Such an assumption leads naturally to a total cross section with increases linearly without limit (Bjorken et al, 1970) provided no boson exists. Thus, even though our data favors the continued scaling of vW_2, at the 2ó confidence level, a scaling breakdown resulting in a diminished cross section near neutrino energies of 65 GeV cannot be ruled out.

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