UCRL--92930

DE87 009589

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July 3, 1985

Lawrence Livermore National Laboratory

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ABSTRACT. We present the arrival directions of 117 upward-going muon events collected with the IMB proton lifetime detector during 317 days of live detector operation. The rate of upward-going muons observed in our detector was found to be consistent with the rate expected from atmospheric neutrino production. The upper limit on the total flux of extraterrestrial neutrinos > 1 GeV is < 0.06 neutrinos/cm^2-sec. Using our data and a Monte Carlo simulation of high energy muon production in the earth surrounding the detector, we place limits on the flux of neutrinos from a point source in the Vela X-2 system of <0.009 neutrinos/cm^2-sec with E$>$1 GeV.

1. INTRODUCTION

Several groups are currently operating fully-functioning proton-lifetime detectors. There is increasing interest in astrophysical phenomena which may be accessible to their detectors especially the possibility of observing extraterrestrial point sources of neutrinos (or other particles [Ref. 1]). At this conference we have seen two theoretical estimates of the flux of neutrinos from the object Cygnus X-3 . T. Walker[Ref. 2] showed that the neutrino flux from Cygnus X-3 is probably too low to be observable even at IMB, the largest proton lifetime detector. In the other talk, A. Dar[Ref. 3] showed that the flux could be high enough to be observable at IMB. In this paper we give preliminary IMB limits on the flux of extraterrestrial neutrinos based on a sample of upward muons collected with the detector.

The current IMB nucleon lifetime limits for 34 decay modes are given in Ref. 4. The detector (see Fig. 1 and Ref. 5) is a rectangular tank measuring 25 m × 18 m × 16 m filled with 8000 tonnes of ultra-pure water. To shield against the cosmic ray background, it is located 600 m underground (1570 mwe), in the Morton-Thiokol salt mine near Painseville, OH. A system of 2048 phototubes (PMTs) arrayed on the six faces of the tank detects the Cherenkov radiation emitted by charged particles crossing the tank. Thus the device is sensitive to charged "tracks".

One way to study cosmic ray neutrinos with this device is to look for muons produced by high energy neutrino interactions in the rock surrounding the detector as shown in Figure 1. We require that the muon produced by the neutrino traverse the entire detector volume; i.e., be "throughgoing". A muon must have $\gtrsim 2$ GeV to cross the detector. This corresponds to neutrino energies of > 4 GeV. At these energies the muons preserve the direction of the parent neutrino to $\sim 10°$.

A typical throughgoing muon illuminates roughly 600 PMTs forming a distinct eliptical pattern of light on the walls. The PMTs nearest the entry point of the muon fire first. The PMTs near the point where the muon exits the detector register the highest light intensities. The data acquisition system records the intensity and arrival time of the light striking each PMT as well as the date and time of the event. We determine the arrival direction of the muon from the recorded data.

The large size of the detector and its ability to unambiguously determine the direction of the muons are distinct advantages in this search.

2. SOURCES OF BACKGROUND

The primary source of background throughgoing muons are cosmic ray interactions in the upper atmosphere, as illustrated in Figure 2a. Muons produced in these interactions penetrate to the depth of the detector at the rate of 2.8/sec. These "atmospheric muons" travel in the downward direction and are eliminated by restricting the sample to muons having zenith angles > 90 degrees.

A more serious background comes from the neutrinos produced in these same interactions (Figure 2b). These "atmospheric neutrinos" penetrate the entire earth in all directions. They produce a slowly varying background of throughgoing muons by interacting with the rock surrounding the detector. This background cannot be eliminated by cutting on track direction. Instead we estimate the effects of this background using a Monte Carlo simulation based on theoretical atmospheric neutrino flux calculations.

3. EVENT SELECTION AND ANALYSIS

The 2048 PMTs are electronically grouped into 8x8 matrices, called "patches". The detector triggers when > 12 PMTs fire in concidence anywhere in the tank, or when there is a coincidence between any two patches having *geq* 3 firing PMTs. The number of PMTs required to trigger is a small fraction of the number illuminated by a throughgoing muon. Therefore, we get a trigger each time a muon enters the detector. Our trigger rate, which is dominated by the passage of downward atmospheric muons, is 230K per day.

Each trigger causes the on-line LSI 11/23 computer to examine the firing times of the earliest 3 PMTs that fired in each patch and to count the total number of PMTs that fired in each patch. Then, in an attempt to remove much of the downward atmospheric muon background, the LSI 11 computes a crude estimate of the muon zenith angle by drawing a line from the earliest patch to fire to the patch with the largest number of firing PMTs. This resulting on-line zenith angle estimate is accurate to about 30 degrees. Events with estimated zenith angle > 70 degrees are recorded on magnetic tape for later off-line analysis. About 34K events/day are recorded in this manner.

Off-line, the analysis procedure obtains an improved measure of the muon track directions by searching for (1) the early grouping of PMTs that mark the muon entry point and (2) the grouping of PMTs recording the highest light levels that signify the exit point. A straight-line fit to the selected PMTs yields an estimate of the muon trajectory accurate to about 5 degrees.

This off-line procedure selects approximately 80 events/day with apparent zenith angle > 80 degrees. Most of these events are high energy atmospheric muons with zenith angles between 80 and 90 degrees. About 6% have zenith angles > 90 degrees and most of these are badly fit downward muons or multiple muons.

To obtain a pure sample of upward muons, we subject the events with apparent zenith angles > 90 degrees to a modified maximum-likelihood fitting procedure that examines the timing and topology of all of the PMTs and determines if the data are consistent with the pattern of Cherenkov radiation expected from a single throughgoing muon having the measured trajectory.

About 3 events/day are determined to be consistent with the upward-going muon hypothesis. These events are examined by physicists using a color plotting system who remove the remaining misfit events and reduce the sample to one genuine upward-going muon event for every 2 to 3 days of live time. Our measured rate for the 117 upward-going muon events collected during 317 days of live detector operation is 0.37 ± 0.03 events/day.

4. THE ATMOSPHERIC NEUTRINO BACKGROUND

We use a 3 stage simulation procedure to estimate the number of upward-going muons expected from the neutrinos produced by the interaction of primary cosmic rays in the atmosphere.

In the first stage of the simulation, atmospheric neutrinos are generated having an angular and energy distribution given by Volkova in Ref 6. The generated neutrinos are allowed to interact in the rock surrounding the detector, producing muons in accordance with a model of the cross sections and angular distributions for muon production by high energy neutrinos. The simulated secondary muons are propagated through the rock, losing energy, until they come to rest in the rock or strike the detector.

The simulated muons that strike the detector are fed to our PMT Monte Carlo program that generates the pattern of firing PMTs according to the Cherenkov formula, while taking into account the effects of muon energy loss, electron pair production and bremsstrahlung. The PMT Monte Carlo program has been extensively tested in detail by comparing simulated downward going muon events with large samples of real downward-going events recorded in the mine.

The output of the PMT Monte Carlo program is a simulated raw data tape which is subsequently analyzed by the same analysis programs and scanning procedures used to obtain the real data sample.

Our studies of 300 days of simulated atmospheric neutrino events result in an expected rate of upward-going muons of 0.34 ± 0.03 (statistical) ± 0.04 (systematic) events/day. The systematic error takes into account the errors in the absolute flux of neutrinos quoted by Volkova (± 5% in the energy region of interest) and the errors in our models of the neutrino cross sections and the composition and density of the rock surrounding the detector.

We note that the rate of upward going muons predicted by the atmospheric model agrees with the data. The model also correctly reproduces the upward muon zenith angular distribution as shown in Figure 3.

5. LIMITS ON AN ISOTROPIC FLUX OF EXTRATERRESTRIAL NEUTRINOS

The absolute difference between the observed and expected number of upward muon events is

measured rate	0.37 ± 0.03 events/day
predicted rate	0.34 ± 0.05 events/day
excess	0.03 ± 0.06 events/day

which is consistent with zero. The 90% confidence limits on the number of excess events is < 0.1 events/day. To convert this into a neutrino flux limit we need to know the neutrino flux necessary to produce 1 event/day in the detector. For the atmospheric neutrinos this number is 0.6 neutrinos/cm^2- sec-str from our Monte Carlo studies. Assuming that the excess extraterrestrial neutrinos have the same energy distribution as the atmospheric neutrinos then our limit on the number of excess upward muons corresponds to an extraterrestrial neutrino flux upper limit of < 0.06 neutrinos/cm^2-sec-str.

6. POINT NEUTRINO SOURCES

Since the secondary muons of energy >2 GeV travel in essentially the same direction as the parent neutrinos, we can search for extraterrestial point neutrino sources by projecting the reconstructed muon trajectories back onto the celestial sphere. Such a source would show up as a localized excess of events above the atmospheric neutrino background.

Figure 4 shows an orthographic projection of the upward muon arrival directions, plotted in equatorial coordinates. There is a general lack of events in the northern hemisphere due to the upward-going requirement. In the southern hemisphere, the distribution is flat with no apparent excess anywhere.

To obtain quantitative limits on the flux from point sources, the following procedure was adopted. We first modified our atmospheric neutrino simulation program so that it generated neutrinos from a particular point on the celestral sphere. We chose the location of the Vela X-2 pulsar (RA=8.5^h; DEC=-45°) as the position of the simulated source. The simulated neutrinos were allowed to interact, producing secondary muons which were analyzed through our upward muon analysis procedure.

We ran two simulations. In the first simulation, the neutrino energy distribution was generated with spectral index γ=3, making it similar to the atmospheric neutrino energy spectrum. The second simulation had γ=2.1, producing a harder spectrum more like the high energy gamma ray spectra reported for some of these objects.

Making use of a file containing the dates, starting times and durations of all of the raw data tapes used in the analysis, the simulation only generated neutrinos during the times that the detector was live.

In the first simulation run, a flux of $0.3E^{-3}$ [neutrinos/cm^2-sec-GeV] produced 90 upward muons that pass our reconstructions. Their reconstructed arrival directions are shown in Figure 5. The position of the source is apparent. The fact that the secondary muons do not exactly follow the neutrino direction, combined with the errors in reconstructing the muon trajectory, smears the distribution of events from the point source. All but one of the simulated events are within 18°of the source.

In the distribution of real events, we find three events within 18°of Vela X-2. If these three events were from the source and if the spectral index of the source was γ=3, then according to the above simulation the three events correspond to a flux of $(0.010 \pm 0.06)E^{-3}$ [neutrinos/cm^2-sec-GeV]. Our integral limit for this spectral index is $\lesssim$0.009 neutrinos/cm^2-sec for E>1 GeV.

The situation for the harder, perhaps more realistic, spectrum with γ=2.1 is different. Unlike the γ=3 case, the majority of the reconstructed upward muons are due to parent neutrinos with energies > 2 TeV implying a large target volume of earth surrounding the detector. We caution the reader that our models of the neutrino cross-section and muon energy loss may not be accurate at these energies. We will certainly do more work in this area in the near future. Nevertheless, according to our current model, the preliminary flux upper limit for the γ=2.1 spectrum is $< 5 \times 10^{-5}\ E^{-2.1}$ [neutrinos/cm^2-sec-GeV] with $< 4.6\times10^{-5}$ [neutrinos/cm^2-sec] having E>1 GeV.

The limits will be similar for other sources having the same declination as Vela X-2. For sources with more northerly declinations, such as Cygnus X-3, the corresponding limits will be less restrictive, due to the decreased amount of time that the source spends below the horizon.

7. CONCLUSIONS

We have set limits on the flux of neutrinos from point sources on the celestial sphere, as well as on the flux of extraterrestrial neutrinos in general. Although no sources were observed, our results place bounds on the allowed flux of extraterrestial neutrinos limiting future models of extraterrestrial phenomena. Our results and procedures should also be useful to those workers who intend to extend the search for extraterrestrial neutrinos, using much larger detectors.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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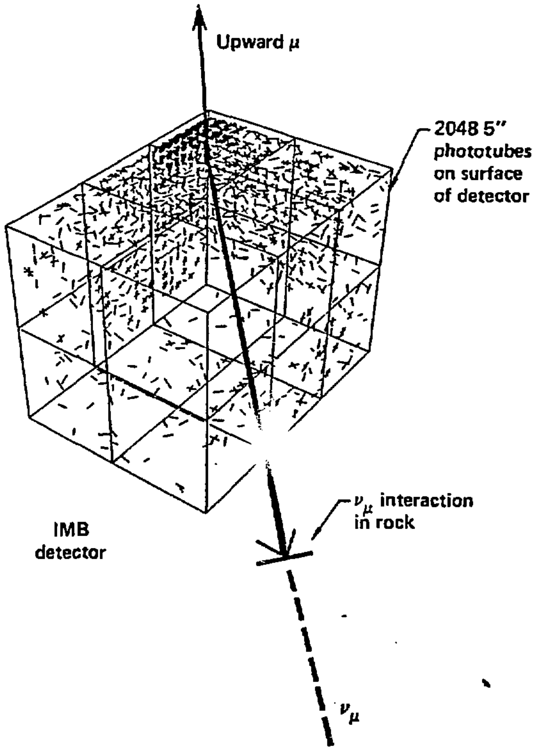

Figure 1 Upward muon detection in the IMB detector. The upward muons are produced by neutrino interactions in the rock below the detector.

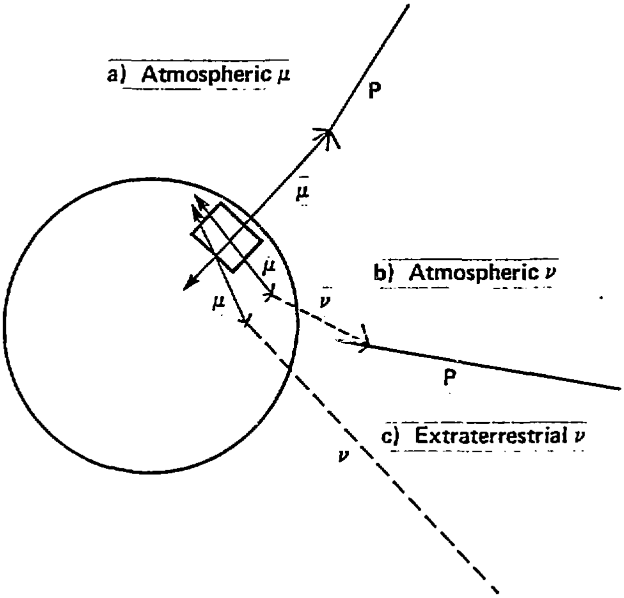

Figure 2 Sources of "throughgoing" muons in the IMB detector.

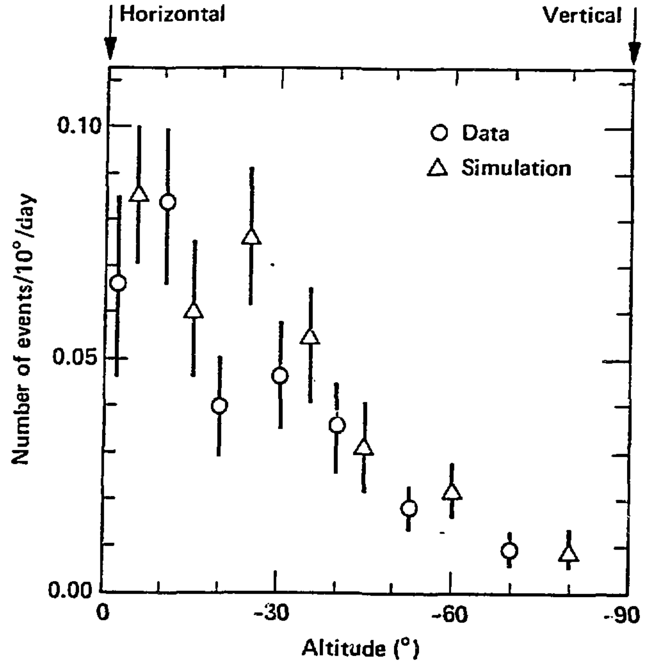

Figure 3 Measured upward muon angular distribution compared with the results of a simulation of muon production from atmospheric neutrinos.

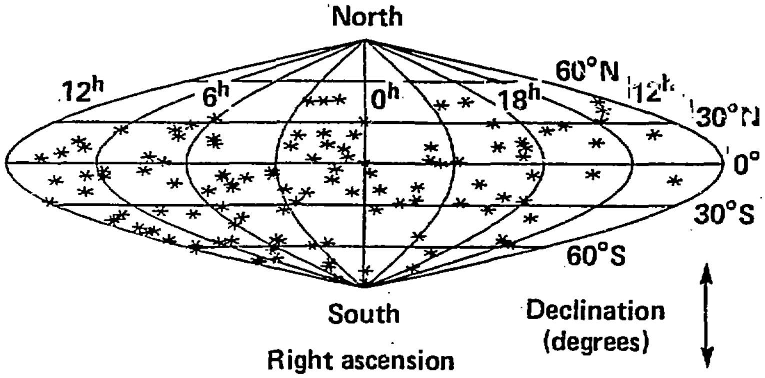

Figure 4 Measured upward muon arrival directions during 317 live detector days projected onto the celestial sphere.

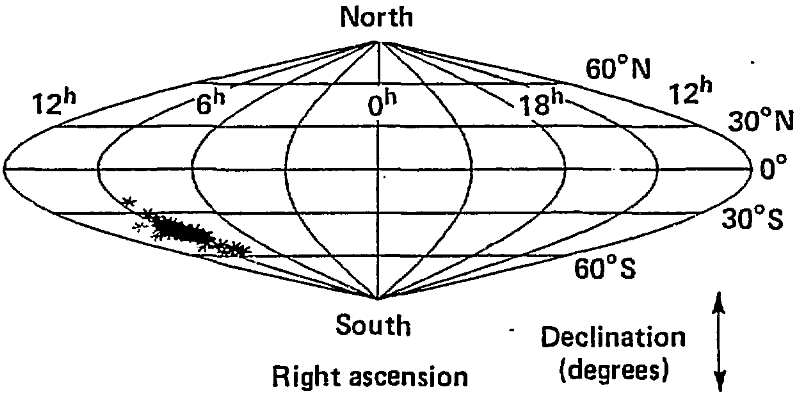

Figure 5 Simulated upward muon arrival directions, during the 317 live days, from a neutrino source located in Vela X-3 having a flux of $0.3E^{-3}$[neutrino/cm^2-sec-GeV].