

The Extraterrestrial Neutrino Flux Sensitivity of Underground and Undersea Muon Detectors.

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Summary. — The sensitivity of underground and undersea muon detectors to point sources of extraterrestrial neutrinos with power law spectra is calculated from very general considerations. It is shown that this sensitivity depends critically on the spectral slope, but is essentially independent of the muon energy threshold of the instrument out to 100 GeV. Sources with a neutrino flux comparable to the γ -ray flux from Cygnus X-3 would not be detectable underground, and are only marginally detectable by the proposed large undersea experiment, DUMAND. However, fluxes perhaps 100 times higher are possible and these would be marginally detectable underground with MACRO or in the proposed DUMAND Stage II detector, the TRIAD.

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1. — Introduction.

For many years high-energy particle detectors have been placed underground to study the penetrating components of cosmic rays. It has always been recognized that these instruments might detect high-energy neutrinos from beyond the solar system, but measured event rates have been consistent with what was expected from neutrinos produced by the interaction of primary cosmic rays in the upper atmosphere ⁽¹⁾.

More recently, larger and better instrumented detectors have been built

⁽¹⁾ F. REINES, W. R. KROPP, H. W. SOBEL, H. S. GURR and J. LATHROP: *Phys. Rev. D*, 4, 3 (1971).

to search for proton decay ⁽²⁾. In addition, it has been proposed that a detector far larger than what is feasible underground can be built in the sea; DUMAND, the deep undersea muon and neutrino detector ⁽³⁾ is now in the first stages of development.

A second stage detector, the TRIAD, has been proposed which can be operational as early as 1987 ⁽⁴⁾. This will have an effective area twice that of any existing or proposed underground instrument.

Proton decay experiments are designed to find particles with a total energy of 938 MeV emerging from a point inside the detector. The major background for these studies results from neutrino-induced interactions. These background events can be used to search for neutrino sources, but a far more sensitive detection of muon neutrinos becomes possible when one allows for interactions outside the detector proper.

Any muon passing into the detector with a zenith angle beyond about $(70-80)^\circ$, depending on depth, most likely was initiated by a neutrino interaction somewhere in the surrounding material. When the neutrino energy is hundreds of GeV muons can result with ranges of several km, so an enormous detection volume is possible at these energies. Further, this volume will increase almost proportionately with muon energy and, when this is combined with the rising cross-section with neutrino energy, a strong preference for higher energies results.

In this paper the sensitivity of this basic type of experiment to point sources of muon neutrinos with power law spectra is calculated using general considerations not limited to any specific instrument. The specific details of the instruments themselves determine the three parameters which govern the event rates from a source of a given flux: the area of the detector A , the minimum detectable muon energy E_0 , and the muon angular resolution $\delta\theta_\mu$. Given these three quantities it is possible to estimate the flux sensitivity of the experiment using the results presented here. This work updates and generalizes a previous study for the DUMAND detector ⁽⁵⁾ and extends the application to underground experiments. The results are consistent with a similar calculation by GAISSER and STANEV ⁽⁶⁾.

⁽²⁾ H. S. PARK, G. BLEWIT, B. G. CORTEZ, G. W. FORSTER, W. GAJEWSKI, T. J. HAINES, D. KIELCZEWSKA, J. M. LOSECCO, R. M. BIONTA, C. B. BRATTON, D. CASPER, P. CHRYSICOPOULU, R. CLAUS, S. ERREDE, K. S. GANEZER, M. GOLDBABER, T. W. JONES, W. R. KROPP, J. G. UNLEARNED, E. LEHMANN, F. REINES, J. SHULTZ, S. SEIDEL, E. SCHUMAND, D. SINCLAIR, H. W. SOBEL, J. J. STONE, L. R. SULAK, R. SVOBODA, J. C. VAN DER VELDE and C. WUEST: *Phys. Rev. Lett.*, **54**, 18 (1985).

⁽³⁾ DUMAND Proposal (Hawaii DUMAND Center, 1982).

⁽⁴⁾ V. J. STENGER: Hawaii DUMAND Center Report HDC-9-85, unpublished (1985).

⁽⁵⁾ V. J. STENGER: *Proceedings of the International DUMAND Symposium*, Vol. 1 (Hawaii DUMAND Center, 1980), p. 190.

⁽⁶⁾ T. K. GAISSER and T. STANEV: Bartol preprint BA-85-9 (1985).

Applying our results, the flux sensitivities of four representative detectors are calculated. The measured muon spectrum which may be expected from a specific source, Cygnus X-3, is presented, where the flux assumed is based on observations of very-high-energy γ -rays.

2. - Calculational procedure.

Basically, any detector deep under the earth or sea is a neutrino telescope. Those which detect muons will be most sensitive to muon neutrinos, which are expected to predominate over other types of neutrinos when the source is high-energy cosmic-ray protons or other nuclei interacting with matter ⁽⁷⁾. Suppose a muon of energy E_μ interacts with a nucleus in the matter surrounding the detector, producing a muon of energy E'_μ at a distance R_μ from a muon detector of projected area A . The muon will lose energy as it traverses matter according to

$$(1) \quad -\frac{dE_\mu}{dR_\mu} = a + bE_\mu.$$

The coefficient a corresponds to ionization energy loss. The coefficient b contains terms for the losses due to bremsstrahlung, pair production and nuclear interactions, important at energies above about 100 GeV. While a and b have logarithmic energy dependences, it is sufficient for our purposes to treat them as constants. We take $a = 0.22$ GeV/m w.e. and $b = 0.3 \cdot 10^{-3}$ /m w.e. ⁽⁸⁾. Then (1) can be integrated to give the muon range (neglecting straggling) when the muon energy at the detector is E'_μ :

$$(2) \quad R_\mu = \frac{1}{b} \ln \left(\frac{a + bE'_\mu}{a + bE_\mu} \right),$$

which can be rearranged to give the muon energy at the point of interaction in terms of the range and energy at the detector:

$$(3) \quad E'_\mu = \left(\frac{a}{b} + E_\mu \right) \exp[bR_\mu] - \frac{a}{b}.$$

While diffuse sources of neutrinos may exist, we will focus here on the possible detection of point sources. Thus the operating mode of each detector

⁽⁷⁾ V. J. STENGER: *Astrophys. J.*, **284**, 810 (1984).

⁽⁸⁾ L. B. BEZRUKOV and E. V. BUGAEV: *Proceedings of the 1979 DUMAND Summer Workshop* (Hawaii DUMAND Center, 1980), p. 225.

will be assumed to be as follows: muons passing through the detector from all directions are continually registered, day and night. Their directions are measured with an angular uncertainty $\delta\theta_\mu$, and other information, such as time of arrival and energy deposited in the detector, is recorded. Any muon arriving from a direction sufficiently away from the zenith to reduce the cosmic-ray muons to negligible proportions, typically 70° , will most likely be from neutrinos. Sources above the horizon might be distinguished from background by directional and time information (period folding). To study a specific source, those muons from a particular angular region on the celestial sphere centred on the source are combined and compared with other control regions. We will take this angular region, or eye, to be a circle of radius θ_0 , at least as large as $\delta\theta_\mu$, the muon angular resolution of the instrument.

Let the differential neutrino flux incident on the detector be $F_\nu(E_\nu)$. The flux of muons of energy E_μ then is

$$(4) \quad F_\mu(E_\mu) = n_A \int_{E_\mu}^{\infty} \frac{dE_\nu}{E_\nu} F(E_\nu) \int_0^{R_\mu^{\max}} dR_\mu \int_0^{x_{\max}} dx \frac{d\sigma_{\nu N}}{dx dy},$$

where n_A is Avagadro's number, $\sigma_{\nu N}$ is the cross-section for $\nu_\mu N \rightarrow \mu + X$ and the Bjorken scaling variables x and y are:

$$(5) \quad y = 1 - \frac{E'_\mu}{E_\nu}$$

and

$$(6) \quad x = \frac{E_\nu}{M} \frac{1-y}{y} (1 - \cos\theta),$$

where M is the nucleon mass and θ is the angle between the incoming neutrino and the outgoing muon. The upper limit on the x integration is determined by the maximum muon angle, $x_{\max} = x(\theta_0)$, where the neutrino is assumed to be coming from the centre of the eye. The upper limit on the muon range R_μ^{\max} is given by (2) with $E_\mu = E_\nu$. The standard model, with QCD corrections, is used for the neutrino cross-section.

Equation (4) applies to neutrinos from a point source. For a diffuse source one must replace $F_\nu(E_\nu)$ with the flux per unit solid angle, and integrate over solid angle. In the case of the neutrinos produced in the atmosphere by primary cosmic rays, this flux is expected to have a $\sec Z$ dependence, where Z is the zenith angle. To compute the event rate for these neutrinos, use the flux per solid angle at Z in (4) and, if θ_0 is not so large as to result in a significant variation in flux over that region of the celestial sphere, multiply by the solid angle $\Delta\Omega = \pi(\theta_0)^2$.

3. - Results for a power law flux.

Let us assume a power law differential neutrino flux of the form

$$(7) \quad F_{\nu}(E_{\nu}) = F_{\nu}(1) E_{\nu}^{-\gamma-1},$$

where E_{ν} is in GeV. Suppose that the minimum detectable muon energy is E_0 . Then the muon flux $F_{\mu}(> E_0)$ above that energy can be calculated by substituting (7) in (4). Let us write

$$(8) \quad F_{\mu}(> E_0) = \varepsilon F_{\nu}(> 1) E_0^{-\gamma}.$$

The quantity ε is then a kind of efficiency for producing muons by neutrinos. It will depend on the muon energy threshold E_0 , radius θ_0 of the eye, and the source spectral index γ . The event rate for a particular detector of area A is simply $A F_{\mu}(> E_0)$.

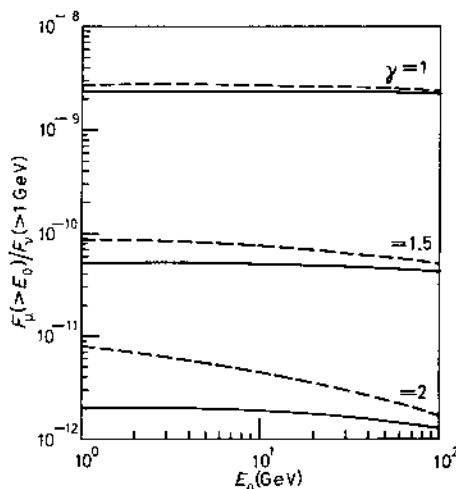


Fig. 1. - The ratio of the muon flux above and energy E_0 to the incident neutrino flux above 1 GeV, as a function of E_0 , for three values of the neutrino integral spectral index γ . — $\theta_{\mu} < 1^{\circ}$, - - - no θ_{μ} cut.

The efficiency ε actually rises rapidly with threshold energy because of the increasing detector volume, but since the neutrino flux above E falls off as $E^{-\gamma}$, the product $E^{-\gamma}\varepsilon = F_{\mu}(> E_0) / F_{\nu}(> 1 \text{ GeV})$ represents a more meaningful measure of sensitivity to a given source. In fig. 1 we plot $F_{\mu}(> E_0) / F_{\nu}(> 1 \text{ GeV})$ as a function of E_0 , for integral spectral indices $\gamma > 1$, 1.5 and 2, and two extreme cases of the maximum muon angle. We note that the sensitivity of

these underground or undersea experiments is strongly dependent on the spectral index of the source, flatter spectra giving many more muons for a given neutrino flux level. A change in spectral index by half a unit changes the muon flux by more than an order of magnitude.

The spectral shape is the primary factor. There is virtually no dependence on the muon threshold energy up to 100 GeV, and the muon angle cut-off is important only for exceptionally steep neutrino spectra and low energy threshold. Limiting the allowed direction of muons causes some loss of events in which the muon does not exactly follow the same path as the incoming neutrino. In our calculation, this is accommodated by the limit on the integration over x being less than unity in (4). As we see in fig. 1, this results in a negligible loss for a fairly flat E_ν^{-1} integral spectrum, but can be a factor of 4 in the case of a steeper E_ν^{-2} spectrum, when the threshold energy is ~ 1 GeV. Because this is mainly an effect from low energies, it is negligible for a threshold of 100 GeV, even for steep spectra.

4. - Application to specific experiments.

We now proceed to compare the capabilities of three representative experiments: IMB ⁽²⁾, MACRO at Gran Sasso ^(*) and two stages of DUMAND, the TRIAD ⁽⁴⁾ and the full array ⁽³⁾. The parameters assumed for each are given in table I. IMB is an existing proton decay detector. The other two are still in planning and development. MACRO would be larger and have a better angular resolution than IMB. The DUMAND TRIAD will have about twice the area as MACRO, but poorer angular resolution. The full DUMAND array is considerably larger and has a better angular resolution than any of the others. But, because of its widely spaced photomultiplier tubes, the minimum muon energy for DUMAND is about 100 GeV, compared with 1 or 2 GeV for the proton decay experiments and 25 GeV for the TRIAD.

Let us consider a specific source. The X-ray binary Cygnus X-3 has now had numerous detections in γ -rays around 1000 GeV and two independent detections above 10^6 GeV ^(10,11) in what are assumed to be γ -rays. Above 1000 GeV, the flux is well represented by

$$(9) \quad F_\gamma(> E) = 3.0 \cdot 10^{-8} E^{-1} \text{ cm}^{-2} \text{ s}^{-1},$$

where E is in GeV. Calculations of the emission of γ -rays and neutrinos by a point source of very-high-energy protons interacting in a surrounding thick shell of matter indicate that, under optimum conditions, the neutrino

(*) MACRO Proposal: Frascati, unpublished (1984).

and γ -ray emission is at least comparable^(10,11); each result from the decay of pions. Suppose, for illustrative purposes at least, that the neutrino flux from a nominal point source is also given by (9). Assume the flux extends down to 1 GeV. Figure 2 shows the number of muons per year above an energy E_μ which will pass into a detector the size of MACRO, 1400 m², when there is either a 1° cut on θ_μ , or no cut at all. To demonstrate the effect of a steeper spectrum, the case for $\gamma = 2$ is also shown, where the flux above 1 GeV is the same as in (9). Rates for the other detectors will essentially scale with their areas. Again we see that the bulk of the muons will have energies exceeding 100 GeV unless the spectrum is steep and the eye is opened wide enough to accept muons well away from the original neutrino's direction.

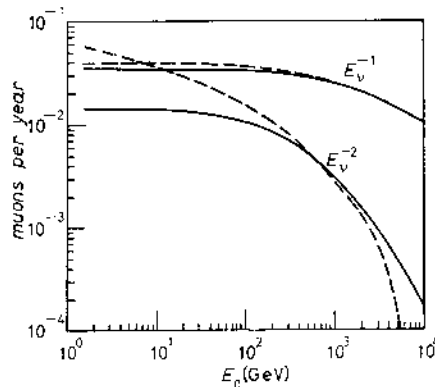


Fig. 2. — The number of muons per year in a detector of 1400 m² from Cygnus X-3, assuming the neutrino flux above 1 GeV is the same as the observed γ -ray flux, for E_v^{-1} and E_v^{-2} integral neutrino spectra, as a function of the minimum muon energy E at the detector. The solid line is for muons within 1° of the neutrino direction; the dashed line takes muons in all directions. Rates for other detectors can be scaled by the relative area. Higher rates are possible from Cygnus X-3 if there is considerable absorption of the γ -rays.

It would appear that the flux of neutrinos needed to produce a detectable signal in any practical underground detector would have to exceed the Cygnus X-3 γ -ray flux by several orders of magnitude. Even the full DUMAND array is marginal at this level. However, it should be noted that it is conservative to assume an equal flux of neutrinos and γ -rays, neglecting the strong possibility of γ -ray absorption in the matter surrounding the source and the steepening of the observed γ -ray spectrum which results from the very substantial interaction of

(10) M. SAMORSKI and W. STAMM: *Astrophys. J.*, **268**, L17 (1983).

(11) J. LLOYD-EVANS, R. N. COY, A. LAMBERT, J. LAPIKENS, M. PATEL, R. J. O. REID and A. A. WATSON: *Nature*, **305**, 784 (1983).

(12) H. LEE and S. A. BLUDMAN: *Astrophys. J.*, **290**, 28 (1985).

10⁶ GeV γ -rays with the 3K background. Rates perhaps 100 times higher are not ruled out by astrophysical considerations ⁽¹³⁾. If we take 10 events per year as the minimum required for a source to be detectable, then the neutrino flux levels for the three detectors are as listed in table I, for $\gamma = 1$ and 2.

TABLE I. - *The parameters for four representative experiments and the neutrino flux above 1 GeV necessary to give 10 events per year, assuming power law spectra with $\gamma = 1$ and 2.*

Detector	Area (m ²)	θ_0 (degrees)	E_0 (GeV)	Minimum detectable flux (cm ⁻² s ⁻¹ above 1 GeV)	
				$\gamma = 1$	$\gamma = 2$
IMB	400	9	2	$3.6 \cdot 10^{-5}$	$3.9 \cdot 10^{-2}$
MACRO	1400	1	1	$1.0 \cdot 10^{-5}$	$1.0 \cdot 10^{-2}$
DUMAND TRIAD	3000	6	25	$4.7 \cdot 10^{-6}$	$4.7 \cdot 10^{-3}$
DUMAND full array	10 ⁶	0.5	100	$1.4 \cdot 10^{-7}$	$1.0 \cdot 10^{-4}$

5. - Discussion.

We have shown an important principle of underground and undersea detection of extraterrestrial neutrinos. Unless the neutrino spectrum is steeper than anticipated, the event rates are essentially independent of muon threshold energy out to hundreds of GeV. This is directly a result of the two factors mentioned above: the rising cross-section with energy and, most importantly, the strong energy dependence of the detection volume. Despite the fact that there are orders of magnitude more neutrinos passing through the detector with energies below 100 GeV, most the associated muons come from neutrinos with higher energy. If the neutrino spectrum is E^{-1} or flatter, there is no particular advantage in having a low muon energy threshold. Some advantage results when the spectrum is steeper, but only if the radius of the eye is increased well beyond 1° to let in the muons at large angles from the neutrino direction. This strategy not only reduces the ability of the instrument to locate a source, but also allows more atmospheric background to enter the detector. When that background exceeds one event per year, a greater signal than 10 events per year is required for detection.

In general, it can be said that the flux from neutrino point sources needs to considerably exceed that observed for γ -rays from Cygnus X-3 for even the largest underground detectors to be neutrino telescopes. Even the much larger undersea DUMAND detector would give marginal event rates in that case.

⁽¹³⁾ G. CHANMUGAM and K. BRECKER: *Nature*, **313**, 767 (1985); *Proceedings of the XIX International Cosmic-Ray Conference (La Jolla)*, Vol. 1 (1985), p. 103.

However, the source luminosity implied by the γ -ray data is about 10^{37} erg s $^{-1}$ which, while considerable by ordinary stellar standards, is still well below limits from astrophysical considerations. A source luminosity perhaps 100 times higher cannot yet be ruled out, and this would produce a marginally detectable flux underground while giving sufficient events in DUMAND to begin doing real neutrino astronomy.

● RIASSUNTO (*)

Si calcola la sensibilità dei rivelatori muonici sotto terra e sott'acqua a sorgenti puntiformi di neutrini extraterrestri con spettri a legge di potenza partendo da considerazioni molto generali. Si mostra che questa sensibilità dipende in modo critico dalla pendenza dello spettro ma è sostanzialmente indipendente dalla soglia d'energia muonica dello strumento fino a 100 GeV. Sorgenti con un flusso di neutrini confrontabili con il flusso di raggi γ da Cygnus X-3 non sarebbero individuabili sottoterra e sono solo marginalmente rilevabili con il grande esperimento sott'acqua DUMAND proposto. Comunque flussi forse 100 volte maggiori sono possibili e questi sarebbero marginalmente rilevabili sottoterra con MACRO o nel rivelatore proposto DUMAND del secondo stadio, il TRIAD.

(*) *Traduzione a cura della Redazione.*

Чувствительность подземных и подводных мюонных детекторов к потоку внеземных нейтрино.

Резюме (*). — Из очень общих рассуждений вычисляется чувствительность подземных и подводных мюонных детекторов к точечным источникам внеземных нейтрино со степенными спектрами. Показывается, что эта чувствительность очень сильно зависит от наклода спектра, но по существу не зависит от мюонного энергетического порога прибора вне 100 ГэВ. Источники с нейтринным потоком, сравнимым с потоком γ -лучей от Лебедь X-3, не могут быть зарегистрированы подземными детекторами и не являются маргинально детектируемыми с помощью предложенного крупного подводного эксперимента ДОМАНД. Однако потоки, в 100 раз большие, оказываются возможными и могли бы быть маргинально зарегистрированы подземными детекторами, тогда как в эксперименте ДОМАНД они производят слишком большой сигнал.

(*) *Переведено редакцией.*

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