Angular and Energy Resolution of the DUMAND Optical Array*

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A start has been made in doing the DUMAND experiment "in the computer". Preliminary results are presented here on the simulation of the response of a cubic lattice of optical detectors in the ocean to muons and hadronic cascades with energies from 5 to 30 TeV. The response is used to reconstruct the muon track in direction and energy and determine the hadronic cascade energy using fairly simple first approximation algorithms. The implications of these results for the three major scientific aspects of DUMAND--high energy neutrino physics, cosmic ray muon physics, and neutrino astronomy are discussed. This work is based on and is an extension of previous Monte Carlo studies /1/ but represents the first time that the simulated detection of events in a realistic array has been attempted.

THE SIMULATION PROCEDURE

The array is taken to be a lattice with a 40 m detector spacing horizontally and vertically, approximately respresenting the current design /2/ The initial position of the event is random within one cell. No consideration has been made of the finite size of the array so the results only apply to the situation where there is adequate "fiducial volume" for the track reconstruction.

For the purpose of determining angular and energy errors the muon and hadronic cascade are treated separately. Let us first consider the muon. The direction of the muon is random. We simulate the various energy-loss mechanisms for the muon as it passes through sea water: ionization, bremsstrahlung, pair production, and nuclear interactions, using the parameterization of Adair and Kasha /3/. All but the first are taken as stochastic processes so no two muons of the same energy will have exactly the same history. We find that pair production is the most important at TeV energies and subject to fewer catastrophic losses than bremsstrahlung or nuclear interactions.

The energy losses along the track are converted into Cerenkov light following the calculations of Belayev et al./4/. The light is then propagated away from the track with appropriate attenuation, including wavelength dependence, to the detector positions. The photon intensities at each detector within several light attentuation lengths of the track are then determined and used to generate, by Poisson statistics, a simulated photoelectron count at each detector. We proceed to act as if we do not know the

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track's position, direction and energy and attempt to determine these from the simulated signals, as if they were real data.

RECONSTRUCTION OF THE MUON TRACK

Roberts has estimated /5/ that a photon intensity of 100 m at the detector will result in a signal of one photoelectron for the current detector design /2/ (2 m^2 collecting area). Background and time-coincidence triggering considerations lead us to suppose that a signal at the 2 photoelectron level will be detectable /6,7/ and, for the purposes of this study, we take this to be our signal threshold. Using the hit detectors a straight line fit in three dimensions is performed with the photoelectron counts as weights. The direction of the fitted track can then be compared with the known direction to determine the error in angle. In Fig. 1 we show the rms angular error as a function of muon energy.

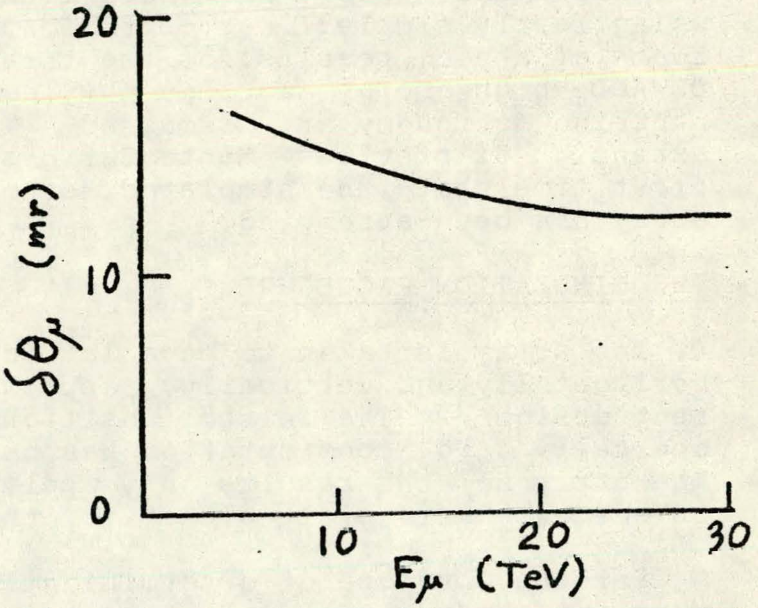

Fig. 1. RMS angular error of muon as a function of muon energy.

We see that angular resolutions better than 15 mr are possible above 10 TeV. We are confident that this can be improved upon with a more sophisticated track reconstruction algorithm.

Next we try to reconstruct the muon energy E_μ. The range-energy relation cannot be used to determine E_μ with any useful precision because of the highly stochastic nature of the energy loss mechanisms at multi-TeV energies and the fact that the muons will not always range out in the array. Instead we exploit the fact that dE/dx increases with energy for muons above 1 TeV because of the dominance of pair production and bremsstrahlung.

As a first iteration on what is bound to be a continuing development of energy calibration techniques the following procedure has been used: the simulated measured photon intensities from the hit detectors are extrapolated back to the source along lines which make an angle of 42°, the Cerenkov angle, with the track. These intensities are "unattenuated" by a factor exp(r/a) where a = 20 m is taken as the attenuation length and r is the distance along the line to the track. We average the intensities when more than one detector signal projects to the same point along the track within 10 m, on the assumption that these signals come from the same source event. Then we sum the projected intensities in 100 m intervals. This gives us a histogram of dI/dx which often contains rather large fluctuations. We then, in essence, compute the average by throwing out the largest fluctuations. The detailed procedure is not worth describing here since it is undergoing constant change. Let it suffice to show some representative results which are conservative and can undoubtedly be improved upon. In Fig. 2(a) we present <dI/dx> as a function of E_μ. The linear rela-

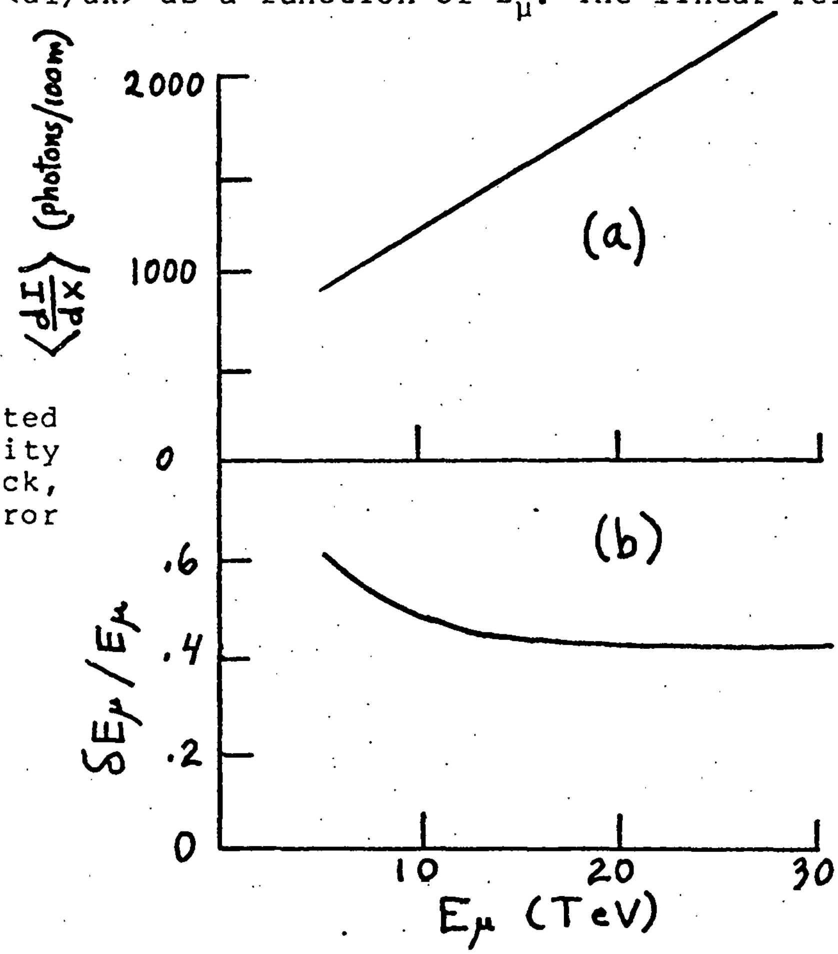

Fig. 2. (a) Projected mean photon intensity per 100 m of muon track, (b) rms fractional error in the muon energy.

tionship between the two nicely confirms the principle that <dI/dx> can be used to measure E_μ. How accurately it can be done, of course, is the big question. As we see in Fig. 2(b), the fractional error in E_μ is approximately constant at 45% above 10 TeV and progressively worse at lower energies where the number of detectors sampling the muon is small. This result is in basic agreement with previous estimates /1/, however, it should be emphasized this applies only for our particular choice of detector spacing and threshold.

ENERGY RESOLUTION OF THE HADRON CASCADE

So far we have not attempted to simulate the hadron cascade in detail. A separate Monte Carlo project is in process for this purpose /8/. As a first approximation we have taken it to be a point source of Cerenkov light. While it is, in principle, possible to obtain directional information from the Cerenkov cone, only a few detectors are illuminated by the cascade and there is insufficient lever arm to use the simple method which we have seen works well for muons. An algorithm to reconstruct the direction of the hadron cascade has not yet been developed but it is clear that the angular resolution will be worse than that for the muon.

The energy of the hadronic cascade, on the other hand, can be determined with reasonable precision. Unlike the muon, all the hadron system energy E_H is dissipated in the array and a larger number of photons is actually collected. We have simply assumed that E_H is proportional to the total photoelectron count and the energy resolution is given be the rms deviation from the mean for an ensemble of tracks of the same energy. The results, as a function of E_H, are given in Fig. 3.

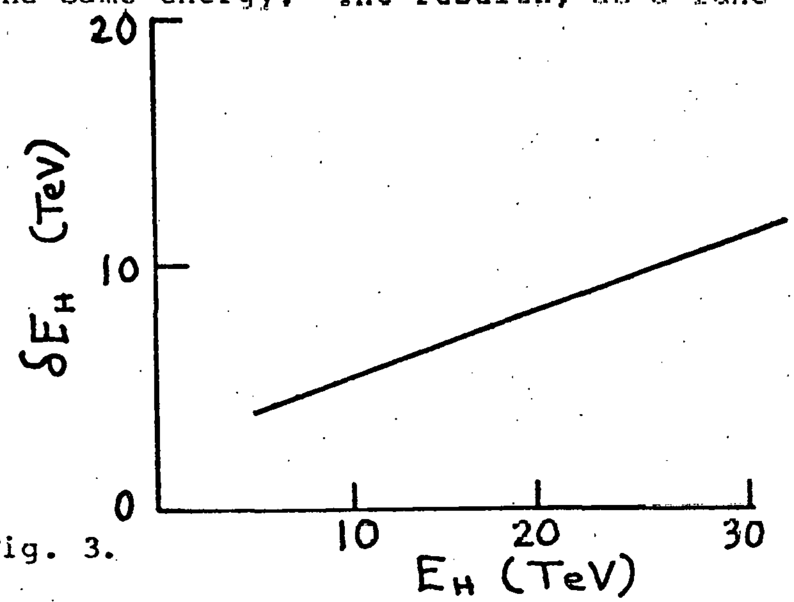

Fig. 3. RMS error in the energy of the hadronic cascade as a function of hadron energy.

IMPLICATIONS FOR THE PHYSICS AND ASTRONOMY OF DUMAND

A large project such as DUMAND cannot be justified on the basis of one experiment or one observation alone. Fortunately there are a number of fundamental experiments in high energy physics and cosmic ray muon physics, and observations in neutrino astronomy which can be made with a "deep ocean laboratory", not to mention many aspects of ocean science which can be explored once there exists a power and signal cable 5 km under the surface.

Our preliminary estimates of energy and angle resolution allow us to make a few statements on the feasibility of these studies. First, the angular resolution of the muon is in the range 10-15 mr. This will enable the location of any point source of neutrinos which may be discovered to a fraction of 10^{-5} of the celestial sphere. This also has a important impact on the ability to detect a point source above an isotropic background.

The errors in muon and hadron energy determine the sensitivity of DUMAND to the effects of the W-boson propagator in events induced by atmospherically-produced neutrinos. We study this by measuring $y = E_H/E_\nu$, where $E_\nu = E_\mu + E_H$, for simulated neutrino events. The incoming neutrino is generated according to an $E_\nu^{-2.8}$ integral spectrum with a minimum energy of 10 TeV. The muon energy E_μ and hadron energy E_H are generated assuming a differential cross section which represents the best theoretical prediction at this time. Both the effects of the W-boson propagator and scaling violations in the structure functions are taken into account. Simulated measured values of E_μ and E_H are then generated by chosing them from Gaussian distributions centered at the true values and with standard deviations taken to be $\delta E_\mu/E_\mu = 0.5$ and $\delta E_H = 2.3 + 0.3 E_H$ TeV.

One simple way to see the effect of the W-propagator is to measure the quantity R = (no. of events with $y > 0.5$)/(no. with $y < 0.5$). This is approximately unity for neutrino interactions at current accelerator energies but will be significantly less than unity for DUMAND energies, above 10 TeV. This is complicated by the fact that there will be an approximately 25% contamination of antineutrino interactions ($\text{flux}(\nu)/\text{flux}(\bar{\nu}) = 2$ /9/, $\sigma(\nu)/\sigma(\bar{\nu}) = 2$ /10/) which have a low value of R. Also the steeply-falling neutrino energy spectrum can lead to difficulties of interpretation/1/. In Table I we show the results that we get from our Monte-Carlo study which includes a simulation of the atmospheric neutrino flux. We see that, even with the 25% "contamination of the beam", the W-propagator results in about a 20% effect which should at least be hinted at in the first few hundred events. The expected event rate from atmospheric neutrinos above 10 TeV is 1000 events per year /11/.

Table I. Results on the determination of $R = N(y>.5)/N(y<.5)$ for neutrinos and antineutrinos separately and for a mixed flux of 75% ν and 25% $\bar{\nu}$, for $M_W = 80$ GeV and $M_W = \infty$.

M_W	ν	$\bar{\nu}$	$.75\nu + .25\bar{\nu}$
80 GeV	.72	.36	.63
∞	1.00	.42	.85

A final aspect of DUMAND which we will discuss concerns the possibility of studying multiple muons from very high energy events induced by primary cosmic rays in the upper atmosphere. Elbert has estimated /12/ that there will be 50 events with two or more muons passing through the DUMAND array each minute! Assuming that we can detect these by their time-coincidence, we can attempt to measure the two muon invariant mass. A rough estimate is that we will have 10-100 events per year with Z-bosons at the mass of 90 GeV predicted by theory. The results reported here allow us to estimate the uncertainty in the two muon invariant mass $m_{\mu\mu}$, where

$m^2_{\mu\mu} = E_{\mu 1} E_{\mu 2} \theta^2_{\mu\mu}$. At 90 GeV it is more than 100 %. However it becomes progressively better as $m_{\mu\mu}$ increases above 100 GeV opening up the unique possibility to search for supermassive objects produced in cosmic rays and decaying into two muons.

CONCLUSIONS

In an initial simulation of the response of the DUMAND optical array to the Cerenkov light from multi-TeV muons and hadronic cascades we find a muon angular resolution which is better than 15 mr above 10 TeV. The muon energy resolution is 60 % at 5 TeV but improves to 45 % and is approximately energy-independent above 10 TeV. The energy resolution of the hadronic cascade is given by $\delta E_H = 2.3 + .3E_H$ TeV. With these errors we can detect the presence of the W-boson propagator in deeply inelastic interactions induced by atmospheric neutrinos above 10 TeV in a few month's running with the currently conceived 1 km^3 array. Point sources of extra-terrestrial neutrinos above a few TeV can be located to a fraction of 10^{-5} of the celestial sphere. Mulitiple muon events induced in the upper atmosphere by primary cosmic rays can be studied with the possibility of measuring the invariant mass of any supermassive objects decaying into two muons.

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