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MASTER

GRANDE An Experiment to Search for
Cosmic Gamma Rays and Cosmic Neutrinos

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ABSTRACT

The GRANDE experiment is a "next-generation" detector capable of making significant contributions to the fields of neutrino and γ -ray astrophysics as well as performing important "conventional" high-energy physics investigations. The detector, which covers an area of $250\text{ m} \times 250\text{ m}$, will have excellent coverage for potential sources of ν emission in the southern hemisphere and of VHE and UHE sources in the northern hemisphere. For VHE and UHE showers, the low threshold (10 TeV) and complete coverage for all three shower components (electromagnetic, muonic, and hadronic), are unique. Excellent angular resolution, $\leq 1^\circ$ for ν 's and $\leq 3^\circ$ for γ -rays, large acceptance, good energy resolution, and wide energy sensitivity will permit detailed studies of the observed signals enabling a quantitative confrontation with theoretical predictions. The detector and its capabilities will be described.

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There has been great excitement recently in the fields of high-energy γ -ray and ν astronomy. The excitement in the Very High-Energy (VHE, 100 GeV-10 TeV) and UltraHigh-Energy (UHE, 100 TeV-10 PeV) domains has been spawned by the recent detection of Hercules X-1¹ in both TeV and PeV energy ranges, observations of "Venus X-3"², and indications of new particle physics observed in air showers from these sources. Additionally, it has been realized that the existence of UHE sources opens up the possibility of studying particle interactions at energies far beyond that available at terrestrial accelerators.

In neutrino astrophysics, the excitement has been mainly due to the opportune observation of a burst of ν 's from SN1987A in both the IMB³ and Kamiokande II⁴ underground water Cherenkov experiments. Over 60 papers have been written about the 19 events observed in these detectors; the characteristics of these events not only confirm major features of the accepted model of Type II supernova explosions but have also been used to determine a variety of neutrino properties.

Further, high-energy neutrino astronomy probes energetic astrophysical objects where copious production of pions takes place. Very high energy photon production, neutrino observations, and cosmic ray studies must be used to obtain information on energetic hadron production in these objects.

The RANDE (Gamma Ray And Neutrino Detector) facility is a dual purpose experiment designed to search for both VHE-UHE γ -ray and high-energy ν sources; it is based on the well developed water-Cherenkov technique. The conceptual design of the detector is shown in Figure 1. It covers an area of 250 m $\times$ 250 m and consists of two semi-independent detectors: the γ -ray telescope and the ν telescope. The Air Shower Array (ASA) part of the detector consists of two optically isolated planes of upward facing photomultiplier tubes (PMTs) spaced on a 6 m lattice, the top plane to detect the electromagnetic and hadronic components of the air shower and the lower plane to detect the muonic component. The Neutrino Telescope (TNT) part of the facility consists of three downward-facing optically isolated planes of PMTs, with the same lattice spacing, used to reconstruct the direction and energy of upward-going μ 's induced by ν 's below the detector. A brief description of the function and performance of each detector follows.

As mentioned, the ASA is composed of two layers of PMTs. The top layer of PMTs, located 10 m below the surface of the water, also known as the "shower calorimeter" layer, serves two purposes; it permits the determination of the direction and energy of the shower, and the identification of hadrons in the shower. Each particle in the shower that strikes the water produces Cherenkov light which is detected by the PMTs. The amount of Cherenkov light produced depends on the particle's energy, mass, and on the Cherenkov threshold. The Cherenkov equivalent energy, or "visible energy", E_v , of a particle is defined as the energy an electron would need in order to produce the same amount

$E_1 = E$ for high energy hadrons
 $E_1 = E$ for muons
 $E_1 = E$ for gamma rays
 $E_1 = E - 1.02$ MeV for pions
 $E_1 = E/2$ for high energy hadrons > 1.02 MeV

In the GRANDE configuration, about 1 photoelectron is produced for every 1.0 MeV of visible energy. In this case, the energy deposited in the shower calorimeter layer can be determined since GRANDE measures the total energy content of the shower and not just a small fraction of the number of charged particles. It is able to operate at a much lower threshold (about 10 TeV) than can conventional air shower experiments.

The direction of the shower is determined from the timing pattern of the detected Čerenkov light. Since the water Čerenkov technique has never been used in this way to detect air showers, it is important to understand the angular resolution of the telescope. For example, the resolution, defined as the mean of the angular difference distribution, is found to be 0.3° for 10 TeV vertical γ -ray primaries observed at sea level. Table 1 illustrates the results, the statistical accuracy of the resolution is about $\pm 0.05^\circ$.

Since standard γ -ray showers are expected to have little if any Čerenkov light from muons or hadrons, showers initiated by proton primaries of a few hundred TeV have also been used. The angular resolution for these showers was found to be 0.3° . In the table, the showers listed under the event type labeled "proton-no μ " are the same showers as the protons except that the muons and hadrons were ignored; for these showers, the resolution is 0.3° .

In the case of proton primaries, the PMT hits in the muon layer were also used to determine the air shower direction. The result was the same as that observed in the air shower layer, about 0.2° .

Finally, the variation in resolution with zenith angle was studied to search for zenith-angle dependent systematic effects. Proton showers, occurring between 28° and 32° , also gave a resolution of 0.2° .

From this it can be concluded that the water Čerenkov technique gives an angular resolution for a variety of event types of $\leq 0.3^\circ$. The capability of GRANDE for reconstructing air shower directions is about a factor of 3 better than any existing array (giving nearly 10 times better signal to noise) and about a factor of 2 better than any other planned array.

The minimum observable primary energy of GRANDE is about 10 TeV. Even for such low energy showers, it is easy to discriminate against uncorrelated background cosmic ray muons. A conservative estimate of the trigger gate width for the ASA in GRANDE is 1 μ sec. In that time, only about 8 muons will pass through GRANDE, spread out over the entire detector. These muons will deposit about 10 pe's in about 15 PMTs. In striking contrast, a 10 TeV γ -ray primary is expected to deposit on the

the size of the detector. The PMTs are arranged in a grid pattern. This is a segmented trigger with easily made discrimination between the hadronic and electromagnetic showers.

Hadronic core identification was studied with a Monte Carlo sample of 100 TeV proton primaries incident on the detector. The detector is the following phenomenological function:

$$T(r) = 1/N_p \cdot \rho_{ph}(r) \cdot N_{ph}(r) \cdot N_{had}(r)$$

was used to test for hadronic cores. The factor $1/N_p \cdot \rho_{ph}(r)$ takes into account the dependence of $T(r)$ on shower size. The second factor is the radial density of photoelectrons and is roughly equivalent to the lateral electron density for conventional air shower experiments. Clearly, the presence of a hadronic core will be signaled by observing an increase in the amount of light near the shower core. In other words, a larger value of $T(0)$.

For each proton event, the response of the detector was simulated both including and excluding all hadrons in the event; the muons were always included since it would be desirable to identify hadrons in their presence. Preliminary analysis of these events shows that ~ 2/3 of the events with a generated hadronic core had a value of $T(0)$ greater than all of the events without the core. Events without an identifiable core had a total hadronic energy less than 1 TeV, or less than 20% of the total electromagnetic component. From this, we see that using even this crude first attempt, we are sensitive to the existence of high-energy hadronic cores over the entire detector area.

The neutrino portion of GRANDE is composed of three layers of downward facing PMTs. Figure 2 illustrates the principle allowing operation of TNT at the earth's surface. A muon resulting from a neutrino interaction in the rock below the detector penetrates the bottom layer, producing a multi-tube coincidence at some time T_1 . The muon continues through the second and third layers at later times T_2 and T_3 . A neutrino event is signaled by observing the sequence of three plane triggers with the following relations.

$$\begin{aligned} T_1 + \Delta t &\geq T_2 \geq T_3 - \Delta t \\ 1 &\quad \text{max} \quad 2 \quad 1 \quad \text{min} \\ T_3 - T_2 &\approx T_2 - T_1 \end{aligned}$$

The first relation requires that the time between the first and second layers is consistent with the passage of a particle travelling at the speed of light. The last relation requires that the particle is travelling upward in a straight line. Detailed simulations of the downward going muon flux, including correlated muons in large showers, resulted in a trigger rate using this simple scheme of about 60 sec⁻¹. If we require the individual PMTs to have more than a few pe's, we substantially reduce this rate since a downward muon usually produces only about 1 pe in each PMT while an upward one produces several. Since most of the background events that trigger TNT are due to large showers of muons caused by VHE cosmic rays, these events will additionally have triggered and been recorded by the ASA.

In this way, the ASA functions as an anti- μ filter for the TNT portion of GRANDE and most of the events that trigger the TNT are of interest to the ASA.

Even though the downward going cosmic ray induced muon flux does not trigger GRANDE at an unmanageable rate, in principle there could be other problems induced by these muons. The ability of the detector to operate in the presence of such a large flux of cosmic ray muons ($\sim 10^5$ per sec) near the earth's surface has been extensively studied including the effects of muon scattering in the rock surrounding the detector. Using Monte Carlo calculations of both hard scattering and multiple scattering it has been shown that muons do not contribute significantly to the upward going muon rate. Further, an examination of relevant experimental data, in particular from IMB, the MUTRON experiment, and the BAKSAN neutrino telescope, also show no excess of upward events more than a few degrees from the horizon. Therefore, the downward flux does not present a significant background for the detection of astrophysical neutrino sources.

Of course, there is an irreducible background to astrophysical neutrino sources due to neutrinos produced in the atmosphere caused by the decay of secondaries in cosmic ray showers. This background is essentially isotropic with respect to any source and therefore is discriminated against by having good angular resolution. There is, however, an inherent minimum resolution caused by both the angular deviation in the neutrino interaction and the muon scattering in the rock on the way to the detector. Figure 3 shows the distribution of the angle between the original neutrino direction and the muon's direction when the muon strikes the detector; the integral distribution is shown for two hypothetical differential power law source spectra with spectral index 2.3 and 3.0. Defining θ_{50} (θ_{90}) to be the angle that contains 50% (90%) of all of the events, the following table illustrates the results for both spectra

$\gamma =$	2.3	3.0
θ_{50}	0.6°	1.3°
θ_{90}	2.2°	4.3°

It can be concluded that a determination of the muon direction with a precision much better than 1° is unnecessary.

The design of the TNT portion of GRANDE was made with this in mind; the goal was a design that would give a muon angular resolution of better than 1° . The final result is an average resolution of $.8^\circ$. This resolution is nearly independent of the zenith angle and the entry point on the bottom plane of the detector.

The irreducible atmospheric neutrino background in GRANDE is calculated assuming an initial muon neutrino and antineutrino spectrum and the standard parton model of neutrino scattering. The resultant muons are propagated through the rock surrounding the detector including all of the relevant energy loss mechanisms and multiple Coulomb scattering. A total of one year of live

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time was simulated yielding 400 events (10 per day) from atmospheric neutrinos. As an example, a 3° cut around the direction of Vela X-1 would yield a background rate of 10.5 events per year.

In fact, given the right circumstances, the "irreducible" atmospheric neutrino background is not really irreducible. It has been clear for a long time that, since the atmospheric neutrino background tends to have a much softer spectrum than that expected from a neutrino source, the signal-to-noise ratio increases with increasing neutrino energy. Thus, it would be beneficial to be able to identify relatively high-energy neutrino interactions. Further, isolation of a subset of the total atmospheric neutrino flux due to very high energy neutrinos would allow study of the weak interaction at high energies.

To examine the energy discrimination of the detector, about 500 muons of varying energies (100 GeV - 10 TeV) were simulated. The increase in Čerenkov light output by high energy muons is due to the rapid rise in muon energy loss due to bremsstrahlung and pair production at $E \sim 1$ TeV. When these distributions are folded with the muon energy distribution due to different parent neutrino spectra, a simple cut on N_{pe} allows the efficient extraction of those events due to very high energy neutrino interactions; Table 2 illustrates the results for various cuts on N_{pe} . For example, a cut requiring $N_{pe} > 200$ removes about 97% of the atmospheric background while leaving about 50% of the signal. From this it can be seen that GRANDE is capable of achieving a high "threshold", long claimed to be a necessity in searching for astrophysical neutrinos, without sacrificing lower energy neutrino events.

In conclusion, in evaluating the capabilities of a water Čerenkov detector such as GRANDE, we have demonstrated several important points:

- 1) Neutrino astronomy is feasible at the earth's surface-it is unnecessary to go underground or underwater.
- 2) The water Čerenkov technique has excellent prospects and is perhaps the first new technique for gamma-ray astronomy in decades.
- 3) GRANDE can be built in just a few years - there are no new techniques or technologies required.

The size of GRANDE is the next reasonable step up for neutrino detection from current underground detectors and is large enough to be very sensitive for gamma-ray studies. Conversely, because of the low fluxes expected from these sources, neutrino astronomy, as well as gamma-ray astronomy, requires such a large size detector. Detection of astrophysical sources of gamma-rays and neutrinos will provide unique information potentially allowing us to understand the nature of the sources as well as the nature of gamma-rays and neutrinos themselves.

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Event Type	Zenith Angle	$\langle N_{\text{int}} \rangle$	$\langle N_{\text{pe}} \rangle$	Resolution
10 TeV gamma	0°	160	300	0.10°
-250 TeV proton	0°	1500	25,000	0.20°
-250 TeV proton (no μ)	0°	1400	20,000	0.13°
-250 TeV proton	28-32°	940	18,000	0.20°

Table 1 Angular resolution of the gamma-ray telescope as a function of event type. The resolution has a statistical uncertainty of $\sim 0.03^\circ$

N_{pe} Cut	Background	Source		Relative Increase in "S/N"	
		γ -2.8	γ -2.0	γ -2.8	γ -2.0
100	62	74	92	1.2	1.5
150	12	26	69	2.3	5.9
200	03	11	52	3.6	17.6
250	01	06	41	4.5	30.2
300	003	03	31	9.8	90.4

Table 2 Fraction of different spectra surviving N_{pe} cut relative to no cut

Figure 1 A schematic of GRANDE.

Figure 2. Timing diagrams of photon and particle arrival times for $\theta_2 = 0^\circ$ and 70° .

Figure 3. Fraction of neutrino-induced muon signal falling within an angle θ , the angle between the incident neutrino and resultant muon. Shown for two values of γ , the assumed source spectral index. Solid line is for $\gamma = 2.3$; dashed line for $\gamma = 3.0$.