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A COMBINED COSMIC RAY MUON SPECTROMETER AND HIGH ENERGY AIR SHOWER ARRAY

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Introduction

A number of very large cosmic ray air shower arrays and underground high energy muon detectors now exist. Cosmic rays have been detected at energies in excess of 10^{20} eV, and individual sources (for example Cygnus X-3) have been conclusively identified as intense emitters of (presumably) gamma rays at energies up to 10^{16} eV. There is clearly a great deal of exciting astrophysics to be learned from such studies, but it has been suggested that there may be particle physics to be learned from the cosmic beam as well[1,2]. Based in particular on the reports of surprisingly high fluxes of underground muons from the direction of Cygnus X-3 modulated by the known orbital period, there have been several suggestions recently invoking stable supersymmetric particles produced at Cygnus X-3, enhanced muon production from high energy photons, quark matter, and "cygnets"[3]. Although the underground muon results have been questioned, it may still be worthwhile to consider the possibility of new physics beyond the standard model with energy scale $(G_F)^{-1/2} \geq$ 0.25 TeV. Halzen et al.[1] have, for example, recently discussed the experimental signatures to be observed from new high energy photon couplings to matter, exchanges between constituent quarks and leptons, and stable gluinos and photinos mixed in with the cosmic gamma ray flux.

We pursue these questions here, and ask how one would clearly detect and measure such particle physics effects at energies above accelerator energies. (It should be recalled that a 10^{15} eV primary cosmic ray energy corresponds to a center-of-mass energy above 1 TeV, and 10^{16} eV photons observed from Cygnus X-3 presumably derive from primary 10^{17} eV protons.) Existing cosmic ray detectors have generally (and necessarily) been designed primarily with size and sensitivity in mind. They have likewise necessarily been fairly crude devices compared to accelerator instrumentation. Yet in order to study the kinds of new physics about which we have speculated, much more detailed instrumentation (although not necessarily much larger areas) will be required.

We describe here a possible detector to search for such effects. We utilize the possibility that point sources like Cygnus X-3 can be used to provide a directional time-modulated "tagged" high energy photon beam[1]. An important characteristic of photon-induced events (at least at low energies) is that the number of secondary muons is significantly lower than for hadron collisions. The number of GeV - TeV muons generated from pion photoproduction and prompt charm decay in primary photon interactions is only a few percent of the number generated by protons. The clearest indication of new physics would then be the occurrence of thresholds above which secondary muon production increases rapidly.

The required detector must be sensitive to the GeV - TeV muon content of cosmic ray showers at energies comparable to and higher than the energies where the Soudan and NUSEX underground detectors have reported excess fluxes of underground muons from Cygnus X-3, and where the Kiel air shower array has reported anomalously high muon contents in showers from Cygnus X-3. On the assumption that these results are confirmed (and there have been serious criticisms of these results), there will be great justification for a much more detailed study of these events. An underground muon detector would require an area large compared to the 10 m^2 areas of the Soudan and NUSEX detectors in order to accumulate reasonable statistics; a depth no deeper than that of Soudan, since the Soudan threshold is sufficiently low to see the effect, and

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deeper depth would presumably reduce the rate; and the best possible angular resolution in order to optimize the signal-to-background ratio from a discrete source. In addition, since the point would be to explore in detail new physics which current underground detectors have not been instrumented to study, the goal would be to measure the energies, multiplicities, and trajectories of both the high energy ($\gtrsim 100$ GeV) underground muons and the lower energy 1 - 10 GeV muons near the earth's surface, and simultaneously observe the electromagnetic shower on the surface.

Detector Description

A schematic diagram of a detector intended to provide correlated measurements of high energy muons deep underground, low energy muons near the surface, and the electromagnetic shower on the surface is shown in Fig. 1. The combination of a large underground transition radiation detector or magnetic spectrometer, a shallow array of muon counters, and an array of electron shower counters on the surface will

i) measure the energy spectrum of the individual high energy μ's;
ii) determine the trajectories and arrival directions of individual μ's, both high energy and low energy;
iii) be sufficiently large in transverse dimension underground to contain the high energy shower;
iv) determine the spectrum and trajectories of the soft μ's; and
v) determine the shower size, lateral distribution, and arrival directions of the cosmic ray primaries on the earth's surface.

High-Energy Muon Detector. At a depth of 600 m, comparable to that of Soudan, the minimum muon energy at the surface required to penetrate to the detector is roughly 650 GeV, while the typical energy at the detector is approximately 100 - 200 GeV. The typical separation of multiple muons produced by secondary pions ($E_\pi \gtrsim 900$ GeV) generated at an altitude h ~ 20 km up in the atmosphere is

$$\ell \sim \frac{\sqrt{2}\, p_t h}{E} \sim 15\ \mathrm{m} \quad ,$$

where we take $p_t \sim 500$ MeV/c as a typical transverse momentum. In order to contain the underground shower with reasonable efficiency, the underground detector should be at least 15m x 15m. This area is 18 - 27 times the sensitive areas of the Soudan I and NUSEX detectors.

We describe two alternatives for measuring the energies and trajectories of the high energy muons: a polyethylene foam/xenon proportional chamber transition radiation detector, and a solid iron magnetic muon spectrometer. The energy dependence of the transition radiation yield is shown in Fig. 2 for three sets of radiator parameters designed to span a wide range of energies[4]. The energy range $10^3 \lesssim E/mc^2 \lesssim 10^4$, where transition radiation detectors have been well tested both in accelerator beams and with cosmic rays, is perhaps the easiest range in which to work. The energies are sufficiently high so that x-ray absorption problems are not serious, and yet

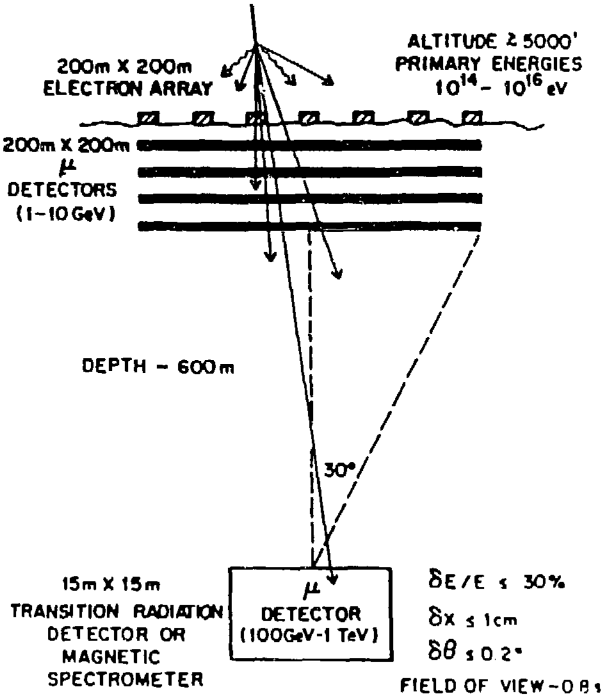

Fig. 1. Detector schematic

the energies are not so high that the x-ray detection becomes difficult and the detector dimensions become large.

A typical radiator for this energy range may consist of 200 polyethylene foils, each 1 mil thick, regularly spaced by 1.5 mm of air. The peak x-ray emission then occurs around 12 keV, and can be detected in a 2 cm thick xenon proportional chamber. Standard foams exist with cell diameters approximately equal to the desired foil spacing, and cell wall thickness equal to the foil thickness. A pulse height distribution from such a commercially available "off-the-shelf" radiator, shown in Fig. 3, is nearly identical to that measured with a radiator of evenly spaced foils. Here the "solid target" distribution gives the energy distribution due to ionization and bremsstrahlung, and the shaded "radiator" distribution gives the sum of ionization plus transition radiation for electrons slightly above the saturation level. Energy resolution $\delta E/E \sim 30\%$ can be achieved with a stack of 10 such xenon chamber-radiator pairs over the range of muon energies 100 GeV - 1 TeV. With chamber resolution of 1 cm over a total length of 3 m, the angular resolution is 0.2^0, better than the deviation in the trajectory due to multiple scattering in the rock.

An alternative to the transition radiation detectors is a solid iron magnet. A horizontal iron toroid with an iron area of 100 m^2 can be constructed out of 1100 tons of 1010 steel. With an inner hole radius of 1.5 m, an outer radius of 5.9 m, a 1.4 m thickness, and minimal air gaps perpendicular to the field, a fairly flat field can be obtained ranging from 22 kG at the inner hole radius to 17.5 kG at the outer radius. An air-cooled coil of 5000 turns of 6 mm diameter copper wire requires 31 A and 36 kW. The particle tracks will be detected in drift chambers set above and below the magnet iron, separated by 2 m. With a ratio of bend angle to Coulomb scattering angle of 5, the displacement of a 1 TeV muon is 1 mm, compared to chamber resolution of 0.2 mm. Costs appear to be comparable for the magnet spectrometer and the transition radiation detectors.

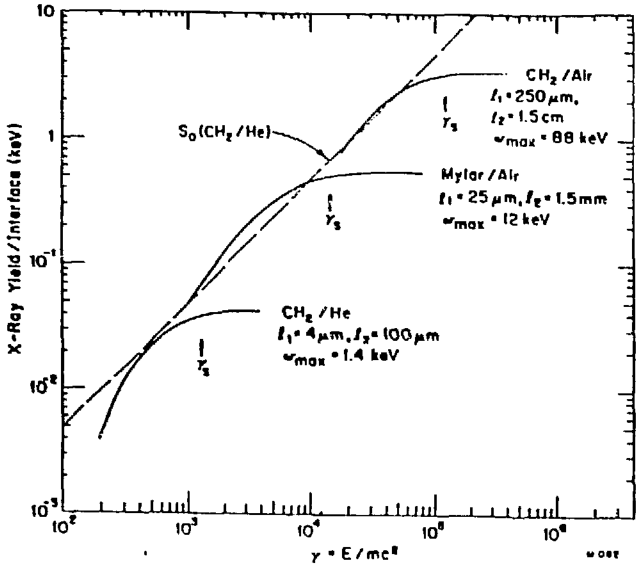

Fig 2. Transition radiation yield vs Lorentz factor for various radiator dimensions.

Surface Electron and Low Energy Muon Detectors.

The bulk of the cosmic ray air showers that will trigger a surface array arrive within about 30^0 of the vertical, corresponding to a solid angle of 0.8 sr. The dimensions required for surface electron and muon arrays to subtend this angle are slightly less than 200m x 200m. These dimensions are comparable to the dimensions of the existing Haverah Park and Akeno arrays, and the new electron and muon arrays currently being constructed at Dugway, and are not much larger than the electron arrays at Los Alamos and Homestake. A source passing directly overhead will then be in the field of view of the combined surface-underground detector for 2 hours a night, compared to the fraction of an hour in the surface-underground telescope currently being operated at the Homestake Mine.

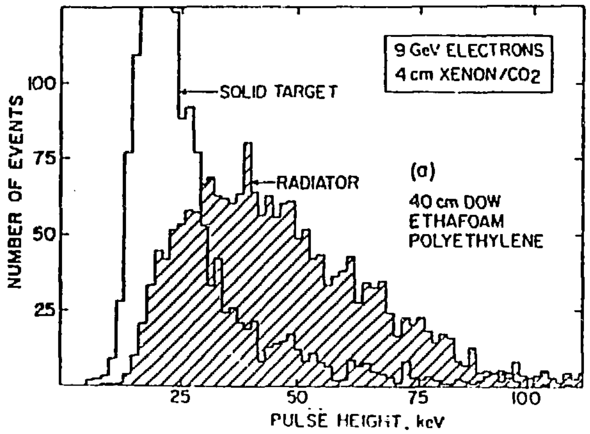

Fig 3. Measured transition radiation pulse height distribution.

In order that the electromagnetic shower threshold be as low as possible, a surface altitude in excess of 5000 ft and counter spacings of 10 - 20 m are desirable. A 200 m x 200 m array of scintillation detectors on the surface can then be sensitive to electromagnetic showers of total energy $E \geq 10^{14}$ eV.

A shallow 1 - 10 GeV muon array requires several layers of counters and dirt or water absorbers. The absorbing layers should be sufficiently thick to eliminate the possibility of low energy "punch-through". Jones[5] has described a scheme for constructing cheap and reliable gas proportional counters in structural steel housings. Such a design was used in Fermilab experiment E613. Using 80 ft lengths of 4" - 6" square pipe with a 5 - 10 mil resistive wire, 1% position resolution (25 cm) can be obtained from the ratios of the signals at the ends of the wires. If several layers are laid down with alternate layers at right angles, 10 - 15 cm resolution is obtained from the counter dimensions. If gas multiplication is kept low, variations due to temperature and pressure changes can be minimized. Based on the E613 experience, the cost appears to be basically the cost of the steel tubing, and the design appears to be simple and workable on a large scale.

If the deep underground detector is used to produce the system triggers, then the trajectory can be traced upwards to the surface electron and muon arrays with a resolution limited by muon multiple scattering in the rock. Allowing $1/2^{\circ}$ for multiple scattering restricts the muon location to 5 m x 5 m on the surface. A resolution of 25 cm for a track penetrating through the layers of the muon array, over a 600 m distance, gives a combined surface-underground angular resolution of 0.02° (neglecting multiple scattering).

Based on the measured Soudan rates, the surface-underground coincidence rate for events involving atmospheric $E > 650$ GeV muons at the surface will be 0.3 sec^{-1}. With the surface arrays and an additional layer of muon proportional counters at a depth corresponding to 25 GeV muons, the vertical $E > 25$ GeV muon rate will be approximately $6 \times 10^{4}\ \text{sec}^{-1}\text{sr}^{-1}$, based on the spectra measured by MUTRON and DEIS. The rate of TeV gamma rays from Cygnus X-3 is approximately 200 $\text{yr}^{-1}(225\ \text{m}^{2})^{-1}$, assuming the source is visible for 2 hours a day; based on the Soudan and NUSEX results, this will also be the rate of underground muons (at least during those periods when the source is active).

Even if the underground muon results are not confirmed, the electron and muon arrays will constitute a photoproduction experiment at energies not accessible to accelerators, and the muon array will provide an excellent soft muon veto for gamma ray astronomy. For 200 underground events per year, the high energy spectrum can be measured and the low energy array can be interrogated to determine the level of any associated soft muon flux; measurement of the high energy muon spectrum differentiates between several models[3], and in particular the showers from 10^{12} eV photon primaries will be below the electron array threshold. If the large angle events measured in the deeper NUSEX detector are due to 50 TeV primaries, then it is possible that a densely-packed high-altitude electron array will be able to see coincidences with the deep underground detector if the surface array threshold is sufficiently low. At 10^{14} eV, however, the electron array can expect to see a rate of 500 events per year, again assuming just two hours per day on the source; all of these events will pass through the shallow muon detector, but only 2 per year will intercept the deep underground detector as well.

Conclusions

In order to study the possibilities of new particle physics at cosmic ray energies, it may be worthwhile to measure the high energy muon spectrum in some detail. If the underground Soudan and NUSEX results on an intense high energy muon flux from Cygnus X-3 are confirmed, it may be possible to use such cosmic sources to produce the cosmic ray equivalent of tagged photon beams, and to measure the rate and spectrum of high energy secondary muons underground together with the low energy muons and the components of the electromagnetic shower on the surface.

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