THE HOMESTAKE SURFACE-UNDERGROUND SCINTILLATORS -- DESCRIPTION

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Two new detectors are currently under construction at the Homestake Gold Mine -- a 140-ton Large Area Scintillation Detector with an upper surface area of 130 m^2, a geometry factor (for an isotropic flux) of 1200 m^2 sr, and a depth of 4200 m.w.e.; and a surface air shower array consisting of 100 scintillator elements, each 3 m^2, spanning an area of approximately 0.8 km^2. Underground, half of the LASD is currently running and collecting muon data; on the surface, the first section of the air shower array will begin operation in the spring of 1985. We describe the detectors and their capabilities.

I. Introduction

Underground, the Large Area Scintillation Detector will be used to 1) search for slow, massive magnetic monopoles with a combination of large area, low dE/dx, low background, and electronic sensitivity to the entire velocity range $10^{-4} < \beta < 1$; 2) study the zenith angle distribution of neutrino-induced and penetrating muons; 3) search for neutrino bursts from stellar collapse events in the Galaxy; and 4) serve as a prototype for a solid, large volume scintillation detector used to search for nucleon decay and ^8B solar neutrinos. The combined surface-underground telescope will be used to 5) measure the multiplicity and transverse momentum distributions of high-energy cosmic ray muons; 6) study the primary cosmic ray nuclear composition near 10^{15} eV; and 7) search for cosmic point sources of neutrinos, gamma rays, and high-energy cosmic rays (for example, Cygnus X-3) with very good angular resolution (3-10 mrad with the combined surface and underground detectors). We describe the design of the detectors here; in an accompanying paper[1], we discuss the initial performance of the LASD.

II. The Underground Large Area Scintillation Detector

The Large Area Scintillation Detector is located at a depth of 4850 ft. (4200 m.w.e.) in the Homestake Mine (Fig. 1). It consists of a hollow 8m x 8m x 16m box composed of 200 30cm x 30cm x 8m liquid scintillation detectors surrounding the existing ^{37}Cl solar neutrino tank of Davis et al.[2]. The detector is sufficiently large to mount a search for magnetic monopoles at the Parker limit (10^{-15} cm^{-2} sec^{-1} sr^{-1}) in 3 years. Each of the 200 scintillator elements is a PVC box lined with teflon (for total internal reflection) containing a low-cost mineral oil-based liquid scintillator developed to have excellent light collection and transmission characteristics, a light attenuation length of approximately 7 m, long-term stability, a high flash point, and low toxicity. In addition, since the same scintillator oil is used in the surface array, the oil maintains its clarity down to very low temperatures. Each detector element is viewed by two 5-inch photomultiplier tubes in coincidence, one at each end. Fast muons passing through the middle of one of the modules produce an average of 350 photoelectrons at each photomultiplier. A particle ionizing even at 0.01 times minimum would thus produce 3-4 photoelectrons at each photomultiplier and still be visible. The low energy threshold is therefore set not by the scintillator light yield, but rather by the background produced by the ambient radioactivity (primarily MeV gamma rays) from the rock walls. We have initially set our thresholds at 1/10 minimum ionizing, or 5 MeV.

The individual detector elements have $\pm$ 1.3 ns time resolution, spatial resolution of $\pm$ 15 cm, and a very low muon background flux. Cosmic ray muons and neutrino-induced muons will typically produce two pairs of coincident photomultiplier tube pulses, one pair as the muon enters the detector and one delayed pair as the muon leaves the detector. The delay between the entering and exiting pulses will be about 25 ns. We can recognize multiple muons passing through a given module by the large pulse height and the mismatch between time differences and pulse height ratios. From the location of the entering and exiting points, the muon direction can be determined to $\pm 3^{\circ}$.

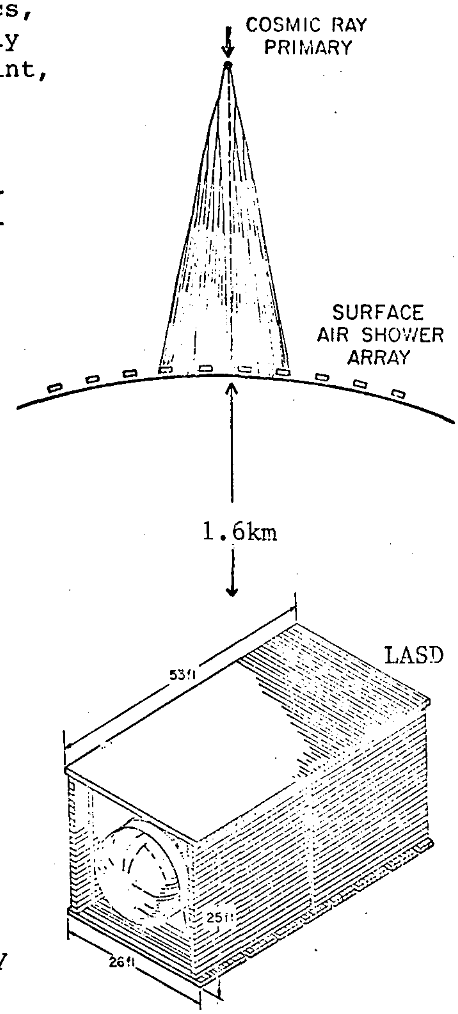

Fig. 1. Surface and underground Homestake detectors.

For a monopole, we expect a pair of slow pulses with width 1 ns/β as the monopole enters the detector and, after a delay of 25 ns/β , a second pair of slow pulses as the monopole leaves. For slow monopoles with $10^{-4} \lesssim \beta \lesssim 10^{-3}$, the delay time between the two entering and exiting pulses will be 25-250 μs. Such long delays can only be correlated in a very low background environment such as that available in a deep mine. The monopole position in each box will be determined from the ratio of pulse heights at each end of the box; the individual pulse heights are then corrected for the position, and the monopole pulse height is determined.

The electronics are designed to permit us to look at both fast muons and slow monopoles. The muon circuitry is currently running on the southern half of the detector. The range of interesting times is from 1 ns to 250 μs. The system is therefore equipped with a fast clock (2.5 ns resolution) which covers the first 500 ns and a slow UTC clock (0.2 μs resolution) to cover the time span thereafter. A 16-pulse (or event) deep memory buffer is associated with each photomultiplier so that multiple pulses for each event can be recorded.

The monopole circuitry is presently being built. It provides the functions of a transient recorder for each photomultiplier, using fast flash ADC's (7 bits, 20 MHz) associated with 2048-byte memories. Five parallel ADC-memory channels are associated with each tube, displaced in time by 10 ns each. When a trigger is seen, the memories are read out for every phototube which fires, giving a record of pulse heights in intervals of 10 ns over a duration of up to 100 μs for a single wall. Individual walls of the detector are triggered independently, so that the total length of the event can be 300 μs, sufficiently long to see slow monopoles ($\beta \geq 10^{-4}$) or low-energy neutrons. A fast (10 ns) muon pulse can then be clearly distinguished from a slowly rising (1/ β ns) monopole pulse; in addition, we measure the flight time across the room, and the individual pulse heights.

The mechanical work on the underground detector is essentially finished. The southern half of the detector has been filled with liquid and turned on. Since Jan. 1985, we have collected 2×10^4 muon events which are currently being analyzed. We are now installing the north-side electronics and filling the remaining detector modules with oil. The detector is expected to be fully operational (including the monopole electronics) in the fall of 1985.

III. The Surface-Underground Telescope -- Composition and Point Sources of Cosmic Rays

The surface array will consist of approximately 100 scintillation detectors, spaced by 15 - 200 m and deployed over an area of about 0.8 km^2 over the underground chamber. The individual detector elements consist of reinforced concrete boxes 4 ft x 8 ft x 2 ft high with 3" thick side walls, covered on top by a 24 gauge galvanized tin cover plate. The inside of the box is lined with styrofoam insulation and an aluminum light reflector. The active detector is 4" of liquid scintillator, designed to have a high flash point and to remain clear at low temperatures. The scintillator is viewed by two 5" photomultiplier tubes operating in coincidence. Twenty-seven detector elements are presently in position and ready to begin operation.

The telescope can operate either in a "prompt" mode in which only the surface elements fire, or in a "delayed" mode in which a trigger pulse from the underground detector arrives approximately 14 μs after the surface array signals. The 14μ s delay is the result of the 5 μs muon flight time from the surface to the underground detector plus the 9 μs signal propagation time along the cable connecting the underground detector and the surface array.

The location of the shower core will be calculated from the locations, pulse heights, and arrival times seen by those detectors firing in the shower. We expect to locate shower cores to within 4 m in the central section of the array and 10 - 20 m in the outer part. Underground, the liquid scintillator elements make it possible to resolve tracks separated by 1 ft; however, the final underground position uncertainty of 2.5 m is determined primarily by scattering in the rock. The angular resolution of the combined surface-underground telescope is then 3 - 10 mrad. The expected surface-underground coincidence rate will be a few hundred per year.

By combining the large air shower array on the surface with the underground detector, we can measure the cosmic ray composition between 10^{14} and 10^{16} eV. Measuring the total electron number N_e on the surface (i.e., the total energy/nucleus) and the multiplicity of high energy ($E_\mu \gtrsim 2.7$ TeV) muons underground (i.e., the energy/nucleon) permits discrimination between primary species in a way that depends essentially on energetics. In order to reach our depth, muons must have roughly 2.7 TeV at the surface of the earth. Such muons can be produced by proton primaries with energies in excess of 10^{13} eV or, for example, by iron primaries with energies above a few times 10^{14} eV. A proton generally gives rise to a single high energy muon while an iron, consisting of a superposition of 56 separate nucleons, has a large probability of multiple muon production, particularly above 10^{15} eV. Our data will thus consist of muon multiplicity and separations underground, and shower size at the surface. For small showers ($E \lesssim 10^{15}$ eV) we expect to observe single muons primarily from cosmic ray protons, while for large showers ($E > 10^{15}$ eV) we expect a mix of single and multiple muons from protons and heavy (nominally iron) primaries.

The combined surface-underground detectors can also be used as a high angular resolution telescope to look for intense point sources of cosmic gamma rays or neutrinos [1].

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