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RESULTS FROM THE SOUDAN 2 DETECTOR *

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Abstract

The Soudan 2 underground detector is a large fine-grained tracking calorimeter comprised of long drift tubes read out by proportional wires. It is surrounded by a proportional tube shield. Preliminary nucleon decay results with 0.5 fiducial kT-yr exposure give 90% CL lower limits of $\tau/B > 4.5 \times 10^{30} yr$ for the mode $p \to K^+\nu$. A search for GUT magnetic monopoles making highly ionizing tracks yielded a 90% CL upper flux limit of $8.7 \times 10^{-15} cm^{-2} s^{-1} sr^{-1}$ for monopole velocities of $\beta > 2 \times 10^{-3}$ in data taken over almost three years.

INTRODUCTION

The Soudan 2 detector is a large, underground, fine-grained, tracking calorimeter which is being built to search for nucleon decay. It was designed to have high spatial resolution and be able to measure the ionization of particle tracks. This makes it possible to also search for other phenomena such as GUT magnetic monopoles traversing the active volume. The detector is located in the Soudan Underground Mine State Park, Minnesota, USA, at a depth of 2100 meters water equivalent. The final detector will have a mass of 960 tons. It will be completed in 1993. Currently 760 tons are operational. Due to its modularity the detector can take data while new sections are being added. Average live times of 70% are typical during this installation period. The detector has been taking physics data since spring 1989 when the active shield became operational and the mass reached 270 tons.

THE DETECTOR

The detector[1-4] is made of $1.1 \times 2.7 \times 1.1 m^3$, 4.3 ton modules which are constructed of 241 stacked corrugated steel sheets. Each module has 7560 slightly conducting, one meter long, 16 mm diameter Hytrel plastic tubes in the hexagonal holes formed by the steel sheets. Copper electrodes, in contact with the tubes, are graded from -9 kV at the center to ground potential at the two ends. This results in a uniform electric field directed parallel to the axis of the tube. The tubes are insulated from the steel by sheets of Mylar and polystyrene.

The whole stack is enclosed in a gas tight

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DISCLAIMER

container which is filled with $Ar - CO_2(85\% - 15\%)$ gas. An ionizing particle traversing a tube yields ionization electrons which drift along the the tube axis under the influence of the electric field with a velocity of approximately $0.6cm/\mu s$. Electrons emerging from the drift tubes are collected and amplified by a proportional counter plane of crossed vertical anode wires and horizontal cathode strips. The anode and cathode signals are fed to ADC's and digitized every 200 ns. Thus, for each point on a track, all three spatial coordinates and the ionization are recorded. The detector has a spatial resolution of ~ 1 cm in all coordinates and records several hundred tube crossings for a typical cosmic ray muon track, allowing it to produce bubble chamber-like displays of events. This capability makes it easy to identify electromagnetic showers, multiple tracks, and other complex interaction topologies from computer displays of the events.

The trigger has a threshold of about 140 MeV/c for muons and 100 MeV/c for electrons. The overall trigger rate is about 0.5 Hz and consists of about 45% through going cosmic ray muons and the rest from random coincidences of γ ray interactions from natural radioactivity in the cavern and detector.

The central detector is surrounded on all 6 sides by an active shield (Fig. 1). This box is made of extruded aluminum proportional tubes 19 cm wide and typically 7 m long. Together they cover an area of 1700 m^2. This shield is used to flag events which are not completely contained in the central detector.

NUCLEON DECAY

The nucleon decay results come from the analysis of 0.5 fiducial kT-yr of data (out of 1.0 fiducial kT-yr currently on tape). The first requirement for an event to be considered as

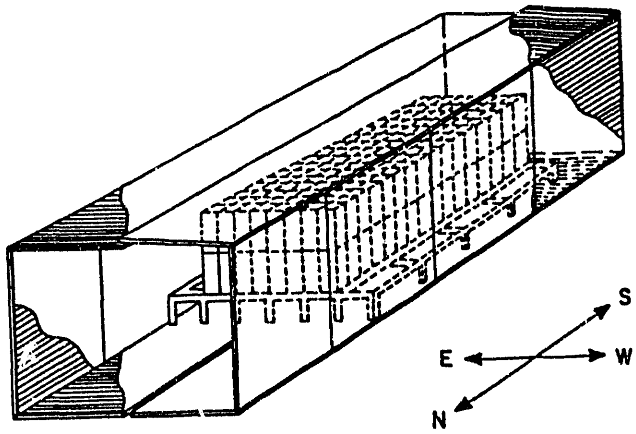

Figure 1. The central detector modules surrounded by the active shield.

a nucleon decay candidate is that it be completely contained in the detector[5]. Events with this characteristic are selected first by a software filter and this reduced set is then scanned with an interactive graphics program by several physicists. The programs and the scanners require that no part of the event be outside of the fiducial volume. The fiducial volume is defined to be 20 cm in from all surfaces. All tracks in an event are examined to see if they could have entered or exited the fiducial volume through one of the cracks between the modules. Finally, the shield is examined to see if it recorded any hits consistent with the central detector event. The shield is designed to reject events caused by muon interactions in the rock which send a neutral particle into the central detector. These muon interactions are almost always accompanied by charged particles which are detected in the shield. 50 events passed all these cuts and these are the set of events which was examined for nucleon decays.

The Soudan 2 detector has good spatial resolution, can find vertices in multi-track events, is sensitive to low energy particles and can accurately measure the ranges of particles. This initial analysis has concentrated on

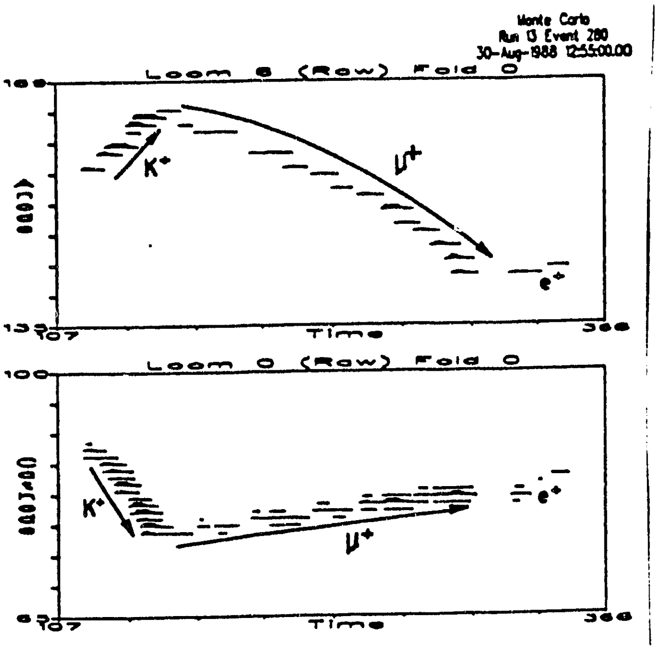

Figure 2. Monte Carlo simulation of a $p \to K^+\nu$, $K^+ \to \mu^+\nu$, $\mu^+ \to e^+\nu\bar{\nu}$ event in Soudan 2.

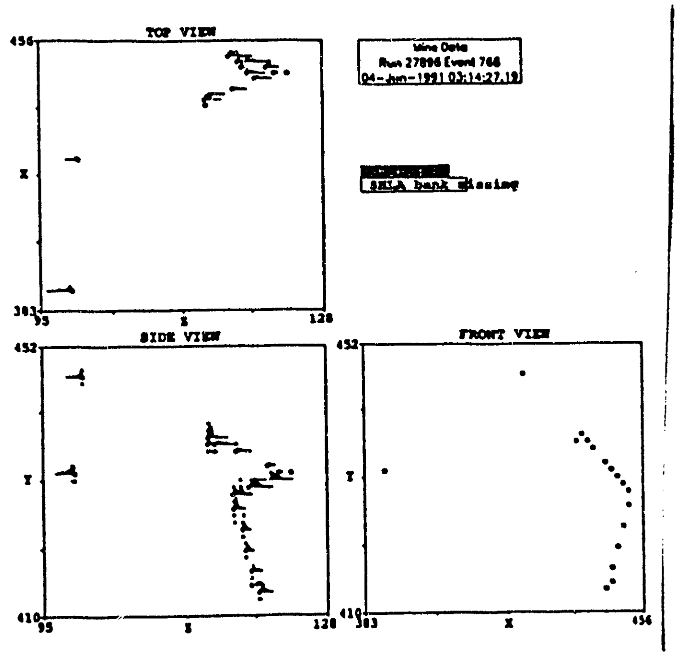

Figure 3. Contained event with the correct topology for a nucleon decay.

nucleon decay modes which take advantage of these strengths. The modes considered were: the SUSY SU(5) favored mode $p \to K^+\nu$, $n \to K^+e^-$, and $n \to K^+\mu^-$ (in each case $K^+ \to \mu^+\nu$ followed by $\mu^+ \to e^+\nu\bar{\nu}$).

The 50 contained events were examined[6] to see if they had the correct topology which would match the decay modes. For example, a $p \to K^+\nu$ event should have a track from the kaon, connected to a track from the muon, connected to a shower from the electron. Figure 2 shows a Monte Carlo event of this decay mode. Given the correct topology, many parameters of the event were then measured; these included the ranges of the K^+ and the muon tracks, the directions of the tracks as determined by the ionization rise, the angle between the K^+ and muon tracks, the number of hits in the shower and the total energy in the event. The expected distribution of these parameters had been determined from Monte Carlo generated events both for nucleon decays and the background neutrino events.

With the parameters of a contained event and the expected distribution of those parameters, a determination was made whether the event was a nucleon decay candidate. With so much information about each event the determination could be made in several different ways and could provide a family of points giving a trade off between low background and high nucleon decay lifetime limits.

From the 0.5 fiducial kT-yr exposure there were two events which had the correct topology for $p \to K^+\nu$, the best one is shown in Figure 3. It was rejected because the 'muon' track was too short and the 'K^+' and 'muon' tracks had the wrong direction. There were therefore no candidates for this mode.

Table 1 shows the results for the three modes studied. These are not yet competitive with other experiments, but after 5 fiducial kT-yr of exposure they will be competitive while the background will be much lower.

Table 1. Soudan 2 nucleon decay preliminary results.

Decay Mode	$\tau/B(90\%CL)$	Background
$p \to K^+\nu$	$4.5 \times 10^{30} yr$	$0.1 evt$
$n \to K^+e^-$	$7.5 \times 10^{30} yr$	$0.03 evt$
$n \to K^+\mu^-$	$6.5 \times 10^{30} yr$	$0.04 evt$

MAGNETIC MONOPOLES

The ionization produced by a magnetic monopole will increase with increasing velocity. Figure 4 shows a schematic compilation of several calculations[7-11] of the ionization versus velocity. However, a monopole of GUT mass can impart little energy to an individual electron, except at very relativistic velocities. From the kinematics of a collision between a very massive monopole and an electron, the maximum kinetic energy imparted to the electron is about 50 MeV at $\beta = 0.95$. On average one hit is produced in Soudan 2 per 12 MeV of electron kinetic energy. Four such hits associated with an otherwise clean track can easily be identified. Muons traversing the detector frequently produce such electrons. At lower monopole ionizations, where a muon and a monopole might be confused, the presence of a knock-on electron can be used to unambiguously reject cosmic ray muons.

The method used to find GUT magnetic monopoles relied on finding straight tracks in the detector which had significantly higher ionization than the average muon, were uniformly ionizing along their length and had no knock-on electrons. All the recorded events were examined by an offline track finding algorithm. For all the tracks which were found the track length and the average summed pulse height per unit track length were calculated. To be flagged as a possible monopole candidate, a track was required to be at least 1.5 m long and to have an average summed pulse height per unit track length of at least four times that of cosmic ray muons. Combining the effects of the relativistic rise and the detector response, an observed ionization of $> 4\times$ the average cosmic ray muon ionization corresponded to $> (8 \pm 2)\times$ minimum ionization. Referring to Figure 4, a monopole velocity can be found corresponding to this ionization range. A value of $\beta > 2 \times 10^{-3}$ was taken as the range over which this experiment was sensitive. This value is conservatively high to account for the uncertainty of the curve in Figure 4 at these velocities.

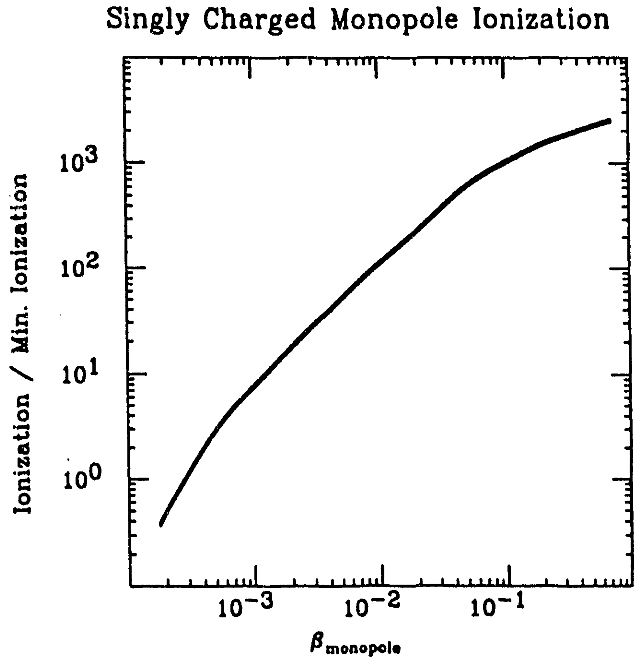

Figure 4. Approximate monopole ionization as a function of β. For this experiment the threshold for high ionization was placed at $10\times$ minimum ionization which corresponds to $\beta > 2 \times 10^{-3}$.

10,254 events were flagged as possible monopoles candidates. For each of these,

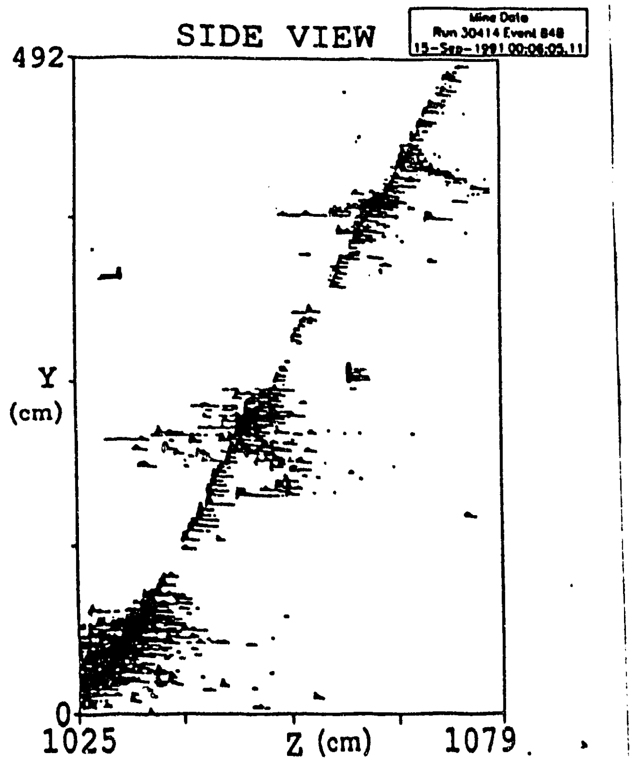

Figure 5. An event rejected due to showers along the track.

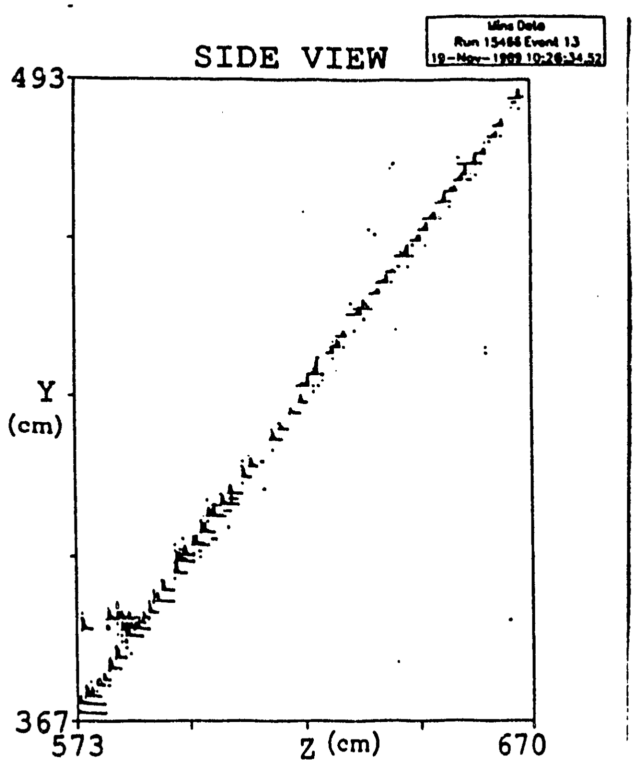

Figure 6. An event with a small knock-on electron associated with the track. This muon track also failed the high ionization cut.

event displays of the raw data were scanned by a physicist using an interactive graphics program. The main criteria for rejection of events during the scan were based on the fact that a monopole of GUT mass would be uniformly heavily ionizing and could not make a visible knock-on electron or a larger electromagnetic shower. No events passed all cuts.

Figure 5 shows a typical showering track. Figure 6 is an example of a muon track which clearly shows a small knock-on electron.

The efficiency of detecting a real monopole was determined by creating a set of fake monopoles from actual cosmic ray muon tracks which were straight and noninteracting. A subset of these was then chosen which traversed the detector isotropically, as expected for sufficiently energetic monopoles. The raw data from these muon tracks were then altered to increase the ionization by various factors to mimic monopoles of various velocities. These fake monopoles were then passed through the software filters and some of them were included in the events being scanned by the physicists. The efficiency for detecting a highly ionizing monopole with track length greater then 1.5 m was 95%.

This data sample was collected over a period of about three years with a total exposure of $2.64 \times 10^{14} cm^2 sr\ s$. This resulted in a limit on the monopole flux of $8.7 \times 10^{-15} cm^{-2} s^{-1} sr^{-1}$ for $\beta > 2 \times 10^{-3}$ (90% CL)[12]. A summary of published monopole flux limits obtained by various techniques[13–19] is shown in Figure 7. Also included is the Parker bound, which is the upper limit on the average monopole flux imposed by the value and rate of regeneration of the galactic magnetic field and the extent to which monopoles would

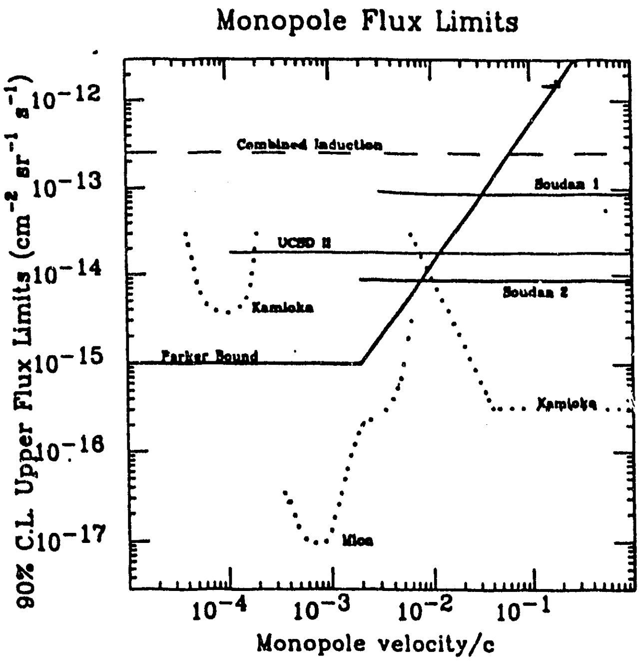

Figure 7. Recent published monopole flux limits. Several techniques are shown. Magnetic induction (dashed line); Track etch (dotted lines): Kamioka, Mica; Gas ionization (solid lines): UCSD II, Soudan 1 and Soudan 2 (this work). The Parker bound upper limit, from galactic magnetic field considerations, is also shown.

remove energy from this field. The present Soudan 2 limit is lower than previously published limits for gas ionization detectors.

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