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The Soudan nucleon-decay programme: A progress report

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Presented by K Heller

Abstract. The Soudan nucleon decay programme consists of Soudan I, a 30-ton tracking *ionization* calorimeter at a 1700 mwe depth, a 100-400 MeV charged particle test beam at Argonne National Laboratory, and Soudan II, a 1000 ton tracking ionization calorimeter at a 1800 mwe depth. Soudan I has been fully operational for 26 days giving a lower limit on the nucleon lifetime of $>2 \times 10^{29}$ years and an upper limit on monopole flux of $<1.8 \times 10^{-3}/m^2$ Sr d. The test beam data gives a Soudan I energy resolution of about 25% for electrons and muons in the appropriate energy range. Soudan II has been proposed and awaits funding.

1. Introduction

Faced with the challenge of investigating nucleon decay to lifetimes of 10^{29} to 10^{33} years, our group adopted the approach of proceeding in stages. Possible difficulties with such an experiment could arise from the construction and operation of a large particle detector underground, unexpected cosmic ray backgrounds at the sensitivities probed, and the recognition of nucleon decay products as distinguished from the backgrounds. Our programme consists of building a 30-ton prototype detector, Soudan I, which is now operational in the Tower-Soudan mine, instrumenting a test beam of 100-400 MeV charged particles at Argonne National Laboratory, which has been used to investigate the prototype detector, and building a 1000-ton detector, Soudan II, which will also be located in the Tower-Soudan mine and will be expandable if necessary. This paper reports the first month of running of Soudan I in its final configuration.

2. The site

The Tower-Soudan iron mine is the deepest in Minnesota and is operated by the State of Minnesota as an underground park. The mine is 160 km north of Duluth, the nearest major city, and 370 km north of the University of Minnesota in Minneapolis. The Soudan I detector is at a depth of 700 m or 1700 mwe. Soudan II will be at 1800 mwe. The flux of cosmic ray muons through Soudan I is 128/hr. This flux

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is low enough not to cause any rate or background problems in the detector while being sufficient to monitor the efficiencies of individual elements of the detector.

3. Soudan I

Those responsible for building, testing, and maintaining Soudan I are: J. Bartelt, J. Blazey, T. Copié, H. Courant, D. Feyma, S. Heilig, K. Heller, S. Heppelmann, M. Hirsch, H. Hogenkamp, C. James, T. Joyce, X. Li, S. Malloi, M. Marshak, B. Neace, J. Osen, N. Pearson, E. Peterson, J. Povlis, K. Ruddick, M. Shupe, D. Wahl, and D. Wicks, of the University of Minnesota; and D. Ayres, J. Dawson, T. Fields, D. Jankowski, and E. May of Argonne National Laboratory. This detector is a tracking ionization calorimeter which, as well as being a tool to investigate technique and background, has sufficient resolution and containment to observe nucleon decay if the lifetime is less than 10^{31} years. The Soudan I detector has been described in detail elsewhere (Courant *et al* 1979; Marshak 1980; Shupe 1981) and is shown in figure 1. The mass is supplied by iron loaded concrete (a taconite-concrete mixture) cast in slabs around thin walled steel proportional tubes. Each slab is 32 cm wide, 4 cm high, and 2·9 m long with 8 proportional tubes of 2·7 cm diameter running the length of the slab. The slabs are stacked to make an array 2·9 m × 2·9 m × 1·9 m. All of the 3456 proportional tubes are horizontal, with each layer perpendicular to the preceding one. The gas for the proportional tubes is a mixture of 91% Ar and 9% CO_2 which is safe for mine use. This gas is pumped through the entire detector, purified, and recirculated. The detector is covered on the top and sides by plastic scintillation counters as shown in figure 2.

The signals from the proportional tubes are processed by the electronics shown schematically in figure 3. The electronics allows us to determine which tubes a charged particle crossed, the pulse height of each signal, and the time the signal

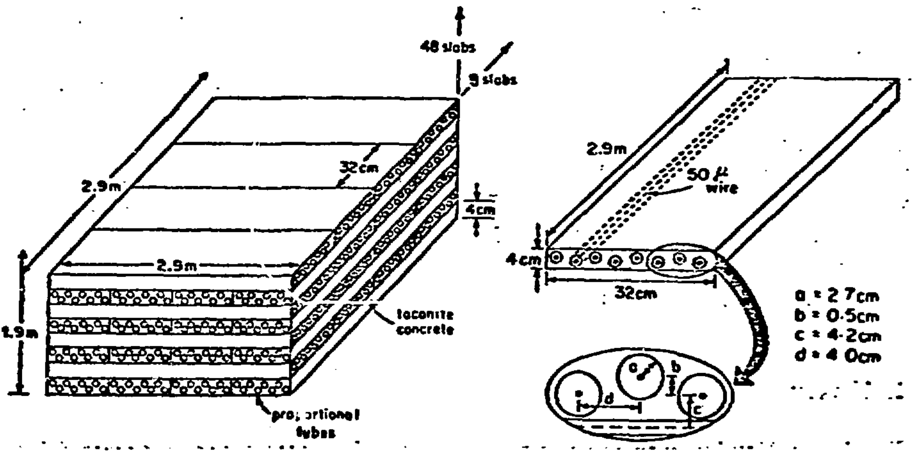

Figure 1. (a) A section of the Soudan I detector array. Alternate layers of proportional tubes are at right angles so that in odd numbered layers the tubes give East-West position information and in even numbered layers the tubes give North-South position information. (b) The geometry of a single slab of the 432 slabs which make

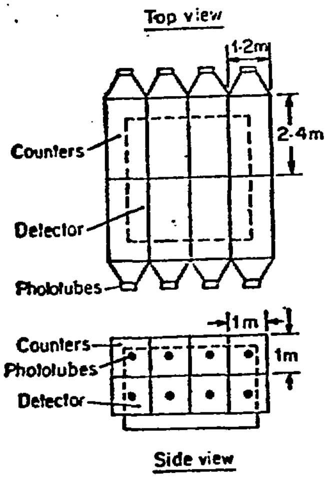

Figure 2. Plastic scintillation counters cover the top and 4 sides of the Soudan I array. Actually the counters overlap each other.

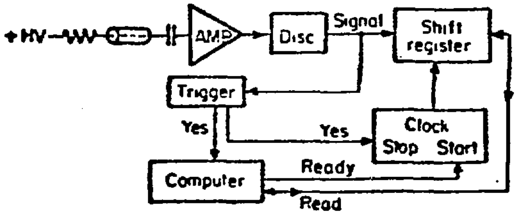

Figure 3. A functional diagram of the major electronics for Soudan I.

arrived. The same information is also available for each of the scintillation counters. Whenever tubes are hit in 3 out of any 4 contiguous layers within 1 μ sec and the event contains at least 5 hits, the computer records the event. Each event is essentially a series of snapshots of the detector from 125 nsec before the event to 7 μ sec after the event in 125 nsec frames. These events are written to disc by our computer. A telephone link to the computer allows us to monitor the detector and sample the data. Full discs are taken to the University of Minnesota for event reconstruction and analysis.

The following sample of events is presented to demonstrate the capabilities of the Soudan I detector. Figure 4 shows a typical event, a muon, from our on-line event display. Pulse heights, represented by numbers at the positions of the hit tubes, have not been corrected for path length through the proportional tubes or amplifier gain variations. The alternate perpendicular layers give the two views of the event which can be used for three dimensional reconstruction. Figure 5 shows the worst type of event for this detector. Because of the spacing between the proportional tubes the detection efficiency is lowest for vertical tracks. Even in such an extreme case however there is no difficulty in recognizing a muon. The observed angular distribution of muons is shown in figure 6 and includes some large angle muons such as figure 7.

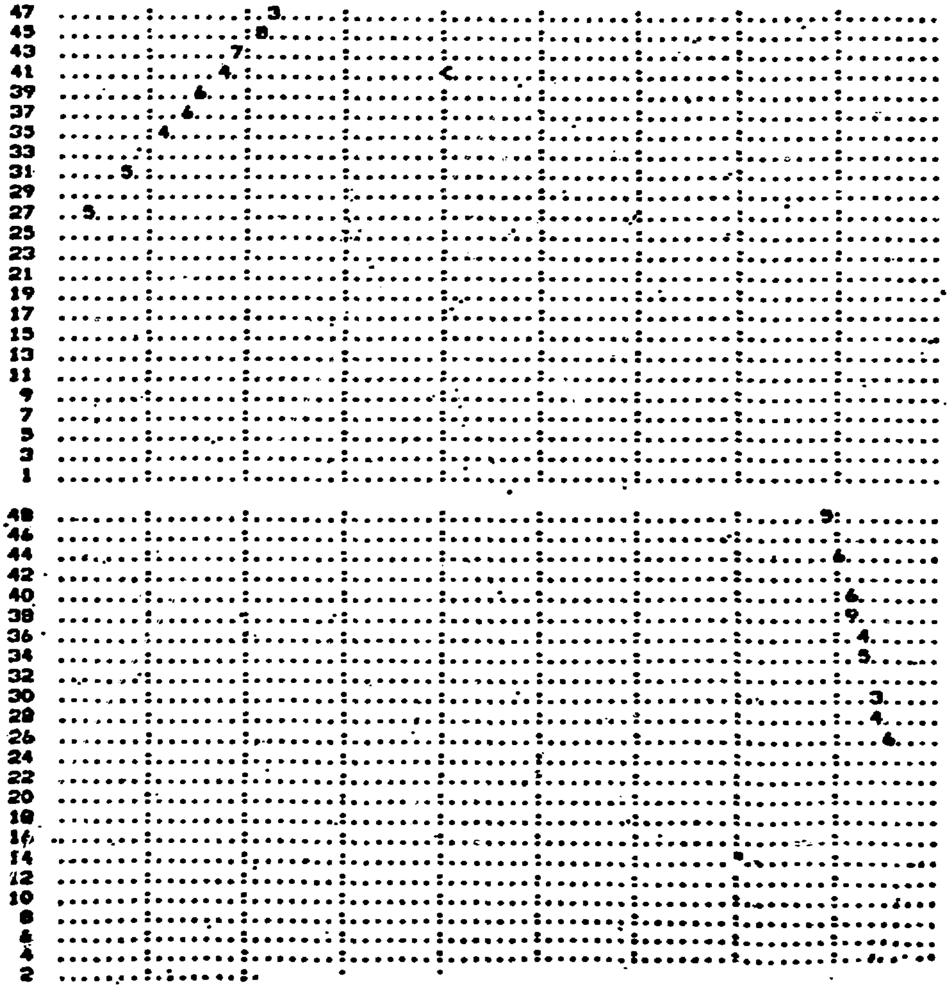

Figure 4. A typical single muon event in the Soudan I detector. The two views represent the alternate layers of the detector array. The numbers represent the uncorrected pulse height of the signals.

A stopping μ^+ can be recognized by its decay $\mu \to e\nu\bar{\nu}$ characterized by a lifetime of 2·2 μsec. This decay is signalled by a delayed hit near the end of the muon track. Figure 8 shows a time distribution for 25 stopping muons from a subset of the data. The distribution is consistent with the measured muons lifetime and demonstrates our ability to identify muon decays.

Multiple muons have also been observed in the detector. Figure 9 shows a typical two muon event while figure 10 shows a much less frequent 6 muon event. The multiple muon tracks are parallel within the resolution of the detector indicating an atmospheric origin. The frequency of multiple muons passing through the Soudan I detector in 26 days is given in Figure 11.

It is the interactions of muons which we are carefully studying to determine the background for various types of nucleon decay detectors. Figure 12 shows a muon initiated electromagnetic shower while figure 13 is a muon interaction with discrete

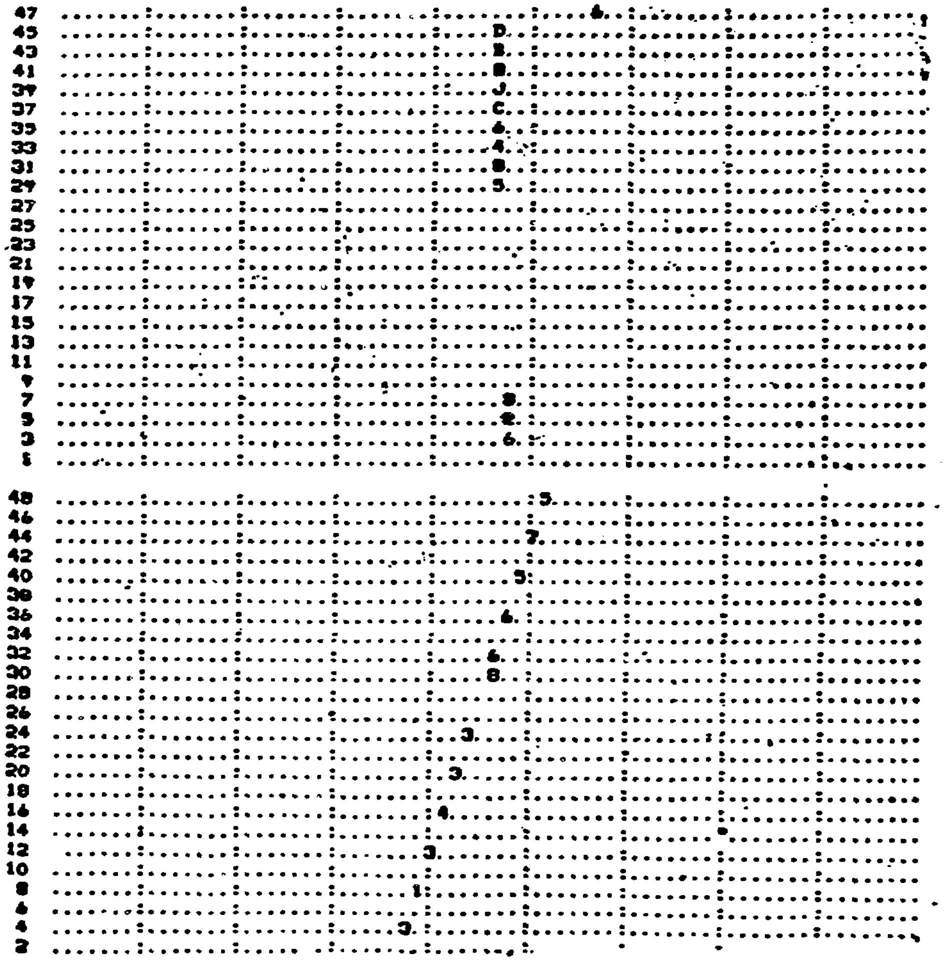

Figure 5. A muon track illustrating the weakness of the detector for small angle tracks. The track passes through several layers between tubes in the odd layers giving a missing section of the track. This weakness however causes no difficulty in muon identification and rejection.

charged particle products. These figures also illustrate that muon interactions can give rise to products emerging at large angles to the incident track. Events with large angle secondaries could be a background for water Cerenkov detectors. Another possible background for all detectors can arise from a neutral hadron entering the detector and interacting or, in the case of a kaon, decaying. These neutral hadrons could be generated by muons interacting in the rock. Figure 14 shows a muon clipping the corner of the detector in coincidence with a contained event well separated from the muon track. Figure 15 shows a muon track through the detector in coincidence with an isolated "V". One can calculate the mass of the neutral parent from the range of the charged particles making up the "V" and the opening angle. Assuming both charged particles are pions, the mass of the parent is consistent with that of a kaon. Because our pattern recognition programmes are still

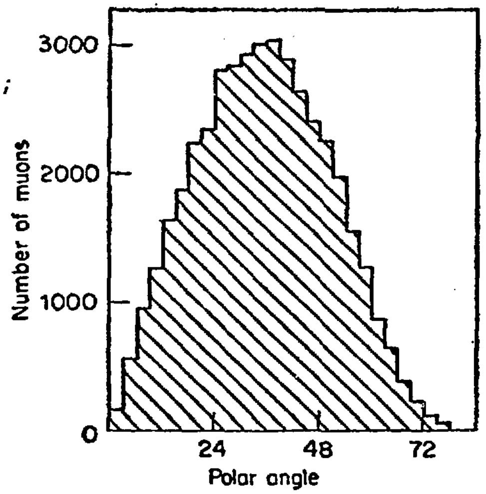

Figure 6. The polar angle of muons detected in Suodan I. The angle from the vertical is measured in degrees.

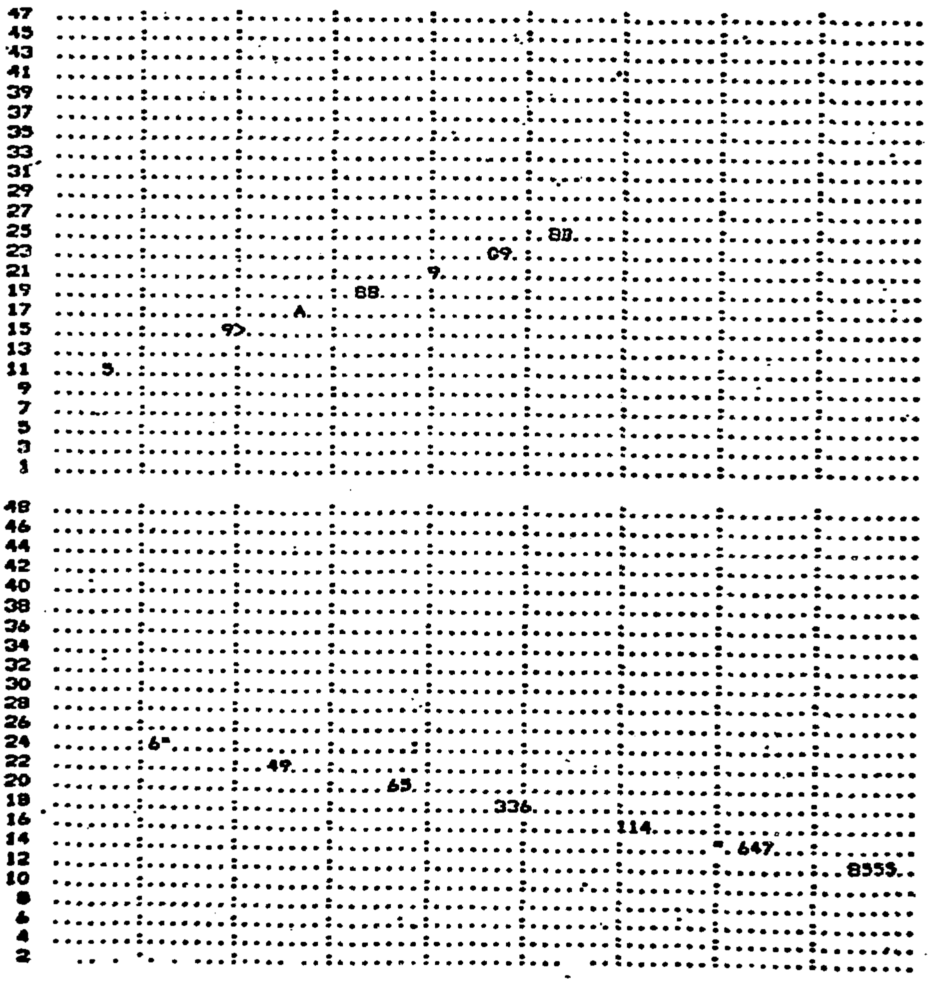

Figure 7. A typical large angle muon track through Soudan I. The polar angle of this event is 80 degrees.

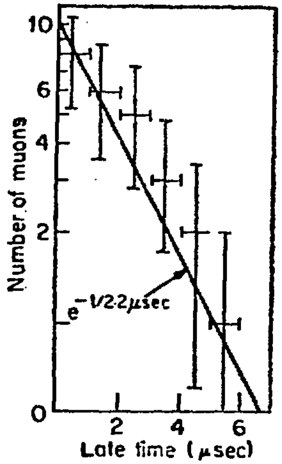

Figure 8. Number of stopping muons with a delayed hit near the end of the track versus the delay time of that hit. The distribution is characteristic of the muon lifetime.

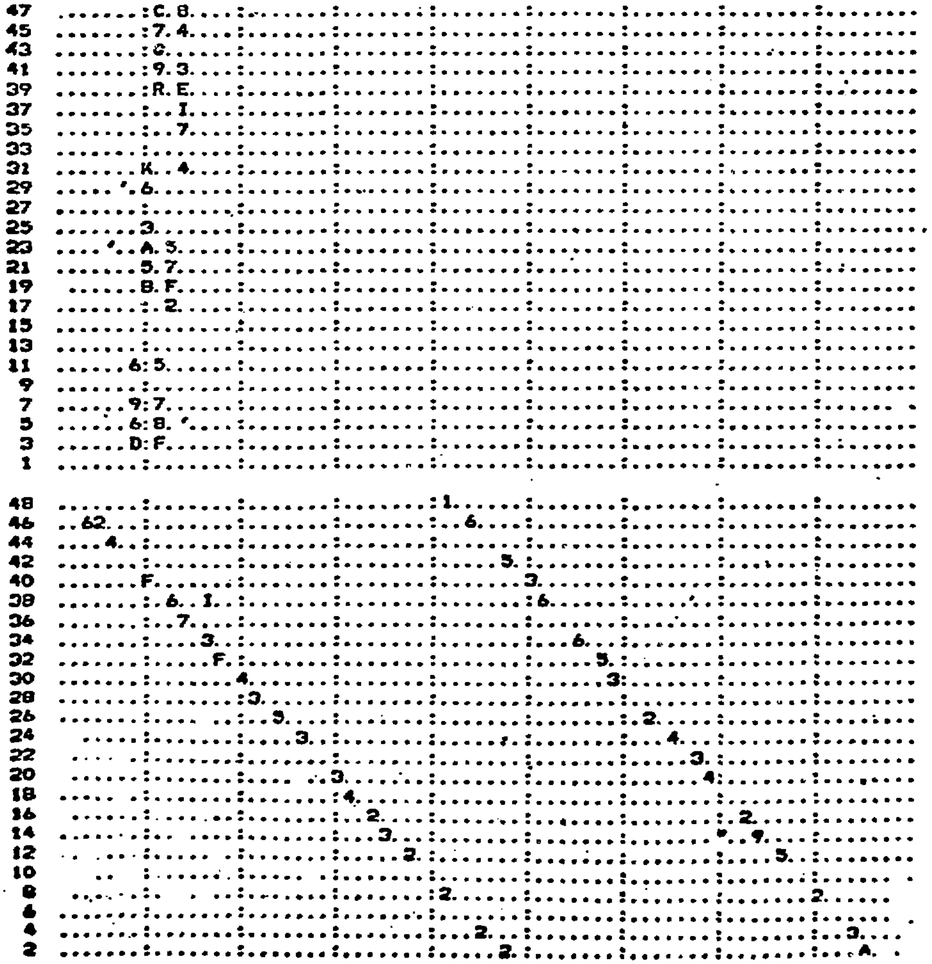

Figure 9. A typical two muon event in Soudan I.

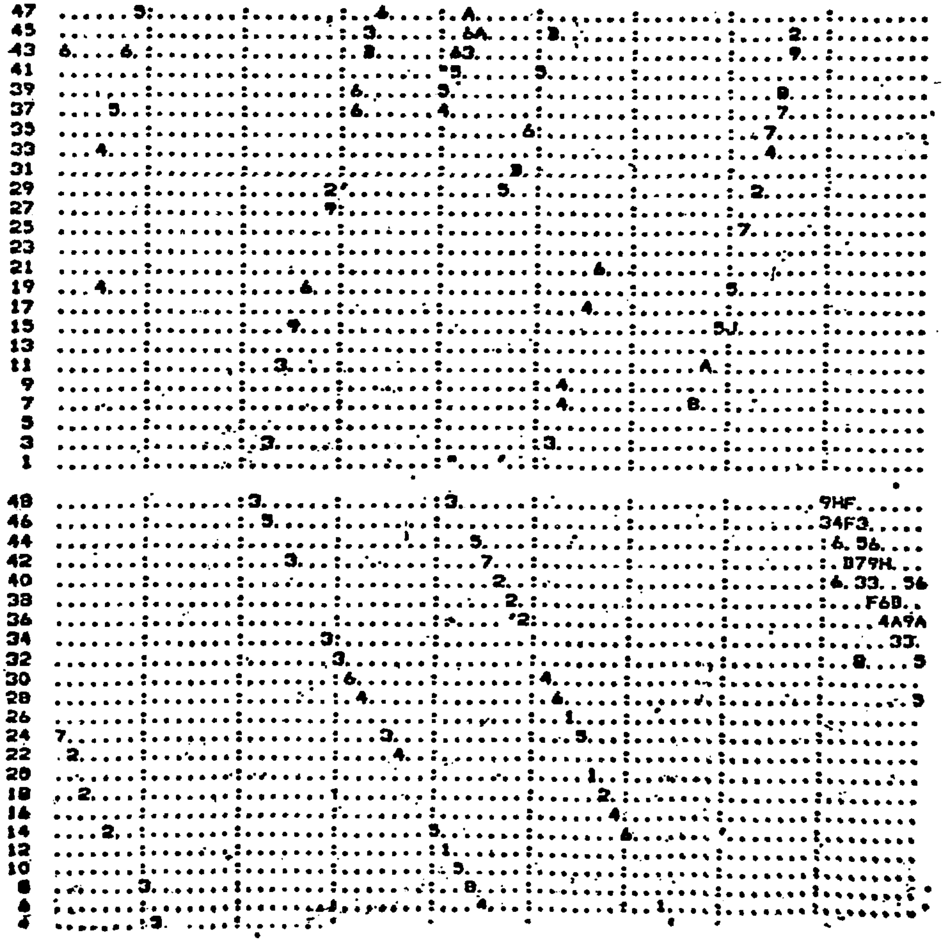

Figure 10. A six muon event in Soudan I. Three of the muon tracks appear close together in the view shown by the even numbered layers but are well separated in the perpendicular odd layer view.

in a primitive state for complicated events we cannot, at this time, quote rates for these processes.

Finally, we have not detected any contained event originating from a 10-ton fiducial mass in the centre of the detector. This gives a lower limit on the nucleon lifetime of 2×10^{29} years at a 90% confidence level for nucleon decays into two or more particles resulting in charged products from our first 26 days of running. As our pattern recognition programmes improve we expect to increase the fiducial mass of the detector by about a factor of two.

We have also not detected any slow, penetrating, ionizing particles with velocities $10^{-4} < \beta < 10^{-2}$. This puts a limit on the flux of such particles, presumably monopoles, of $< 1{\cdot}8 \times 10^{-3}/\mathrm{m}^2$ Sr d at the 90% confidence level compared to the published limit of $< 3 \times 10^{-2}/\mathrm{m}^2$ Sr d Ullman (1981). The published limit was also achieved using proportional counters and presents arguments as to why scintillation counters may not be efficient monopole detectors.

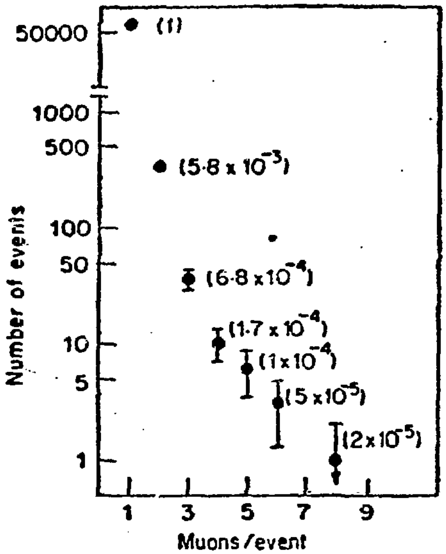

Figure 11. The number of multiple track muon events seen in Soudan I in 26 days. The number in parentheses by each point is the relative frequency. Note the broken scale.

4. Test beam

Modules of the Soudan I detector were exposed to both a positive and a negative test beam at Argonne National Laboratory. The beam momentum was varied from 100–400 MeV/c and the particles were identified by time of flight. Figure 16 is a typical time of flight spectrum for the 250 MeV/c negative beam. Figure 17 gives the measured energy resolution of the Soudan I detector for electrons and muons. The energy of the electrons was determined by the number of proportional tubes hit while muon energy was determined by range. Electrons are easily distinguishable from other particles by their electromagnetic shower. Our analysis of these exposures is continuing.

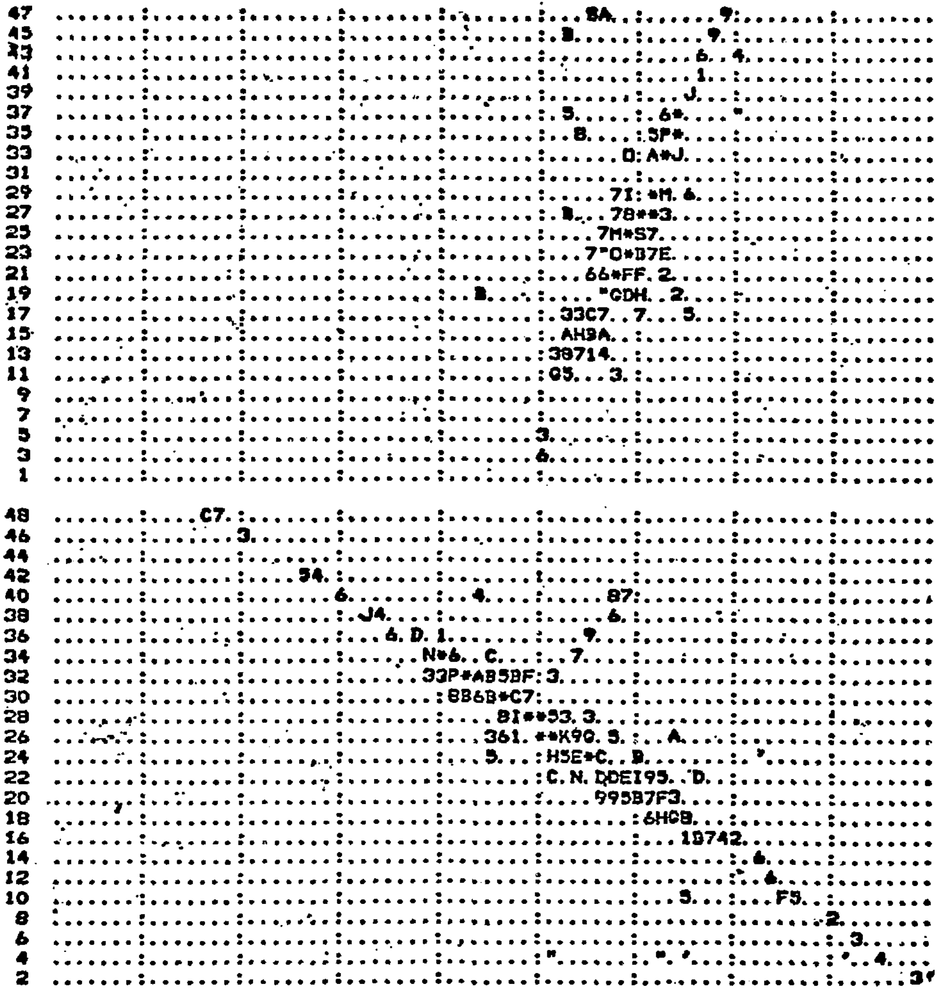

Figure 12. A typical electromagnetic shower induced by a muon in Soudan I. Note the charged track visible in the even view coming from the centre of the shower. This track is at a large angle to the muon track.

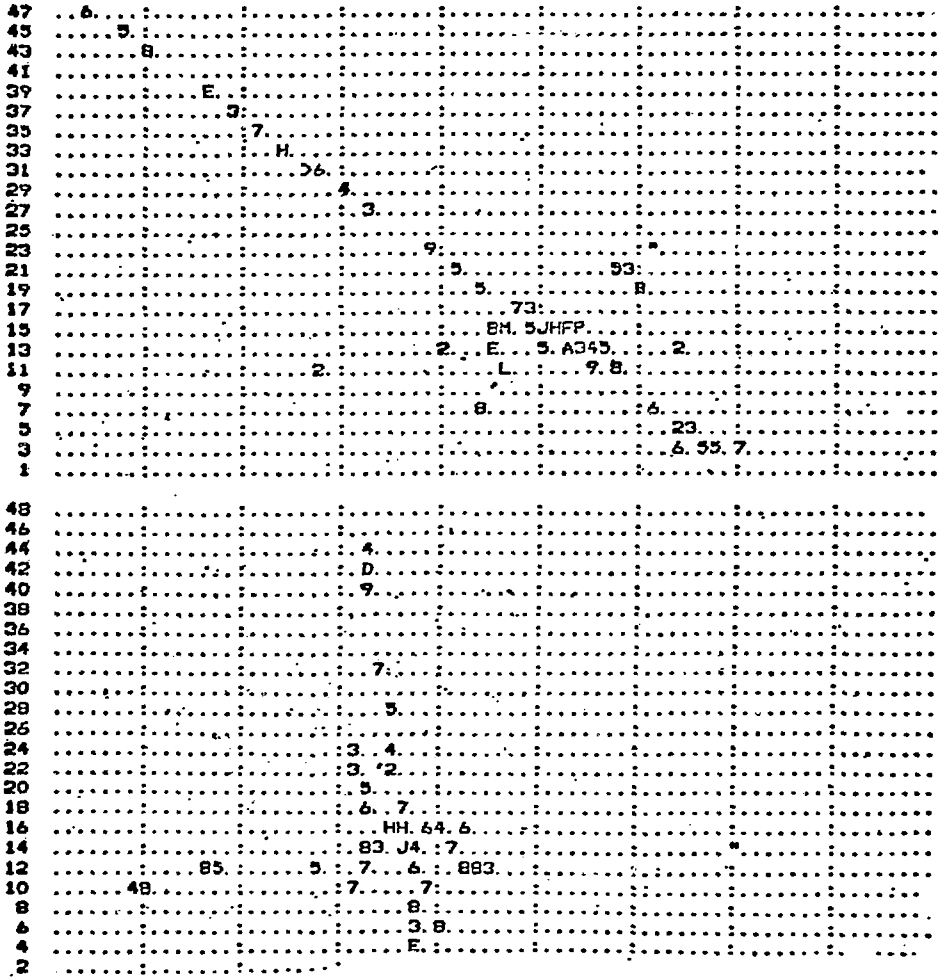

Figure 13. Discrete charged particle tracks originating from a muon interaction in Soudan I. Tracks at large angles to the muon direction are visible in both views.

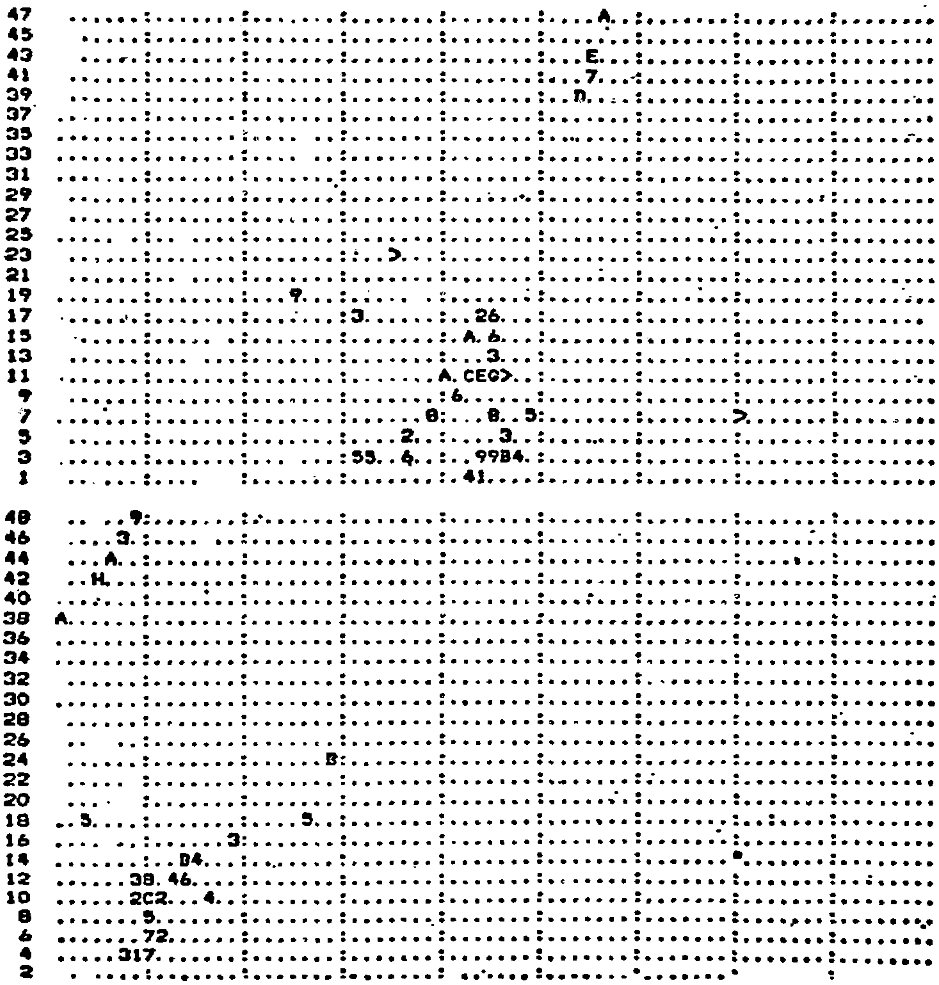

Figure 14. A contained event in Soudan I in coincidence with a muon track clipping the corner from layers 49 to 38.

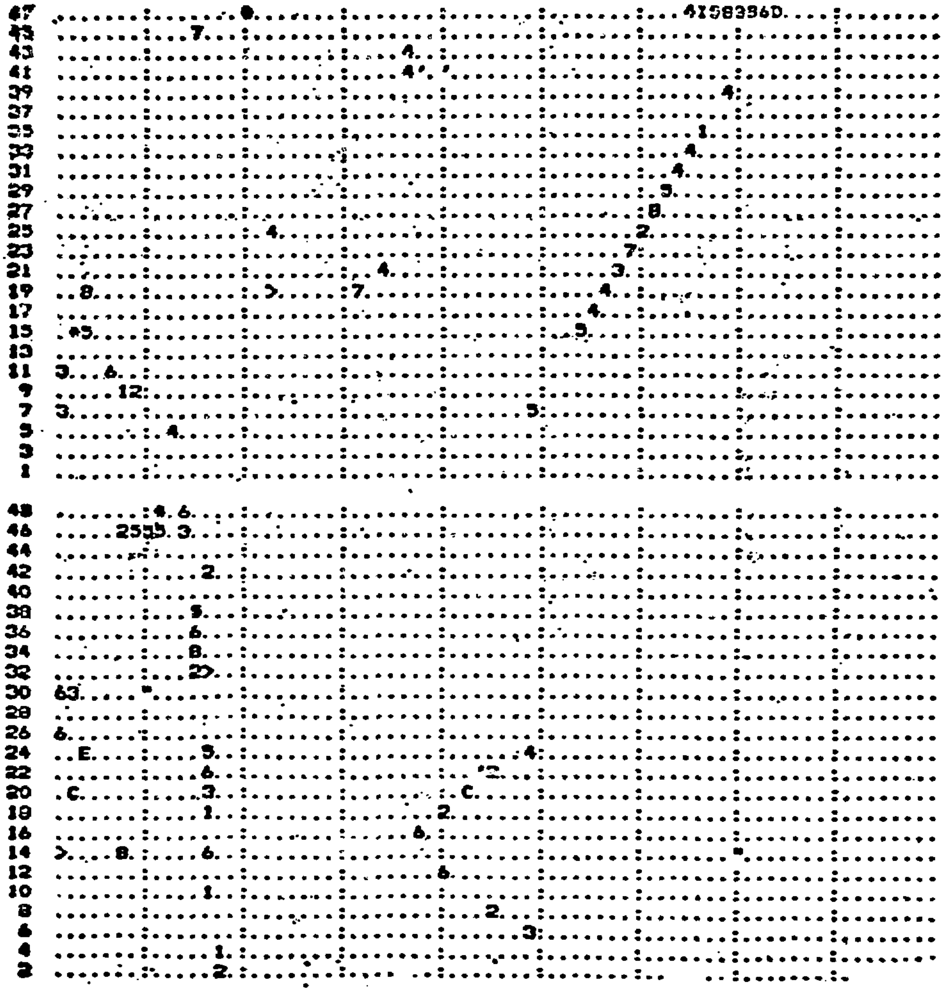

Figure 15. A charged particle "V" in Soudan I clearly visible in the even view. The "V" is in coincidence but cleanly separated from the through going muon track.

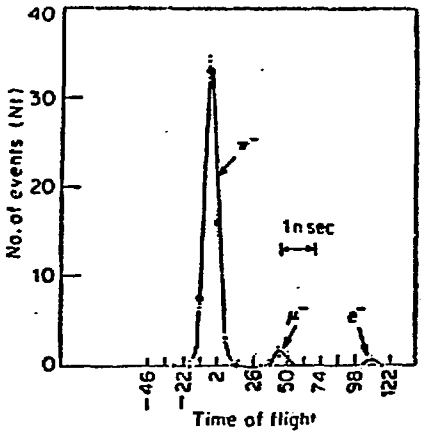

Figure 16. A representative time of flight distribution for the 250 MeV/c negative test beam at Argonne National Laboratory. The units of the horizontal axis are arbitrary but the size of a 1 nsec bin is shown. The pion peak has $\sigma = 200$ p sec.

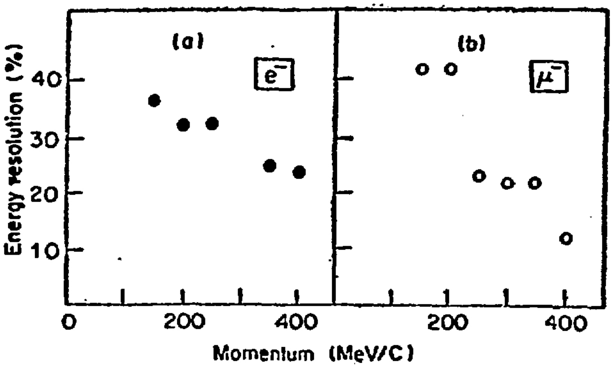

Figure 17. Energy resolution of the Soudan I detector as determined by the Argonne test beam. (a) For electrons the energy is calculated from the number of proportional tubes hit in the electromagnetic shower. (b) For muons the energy is calculated from the range of the straight track.

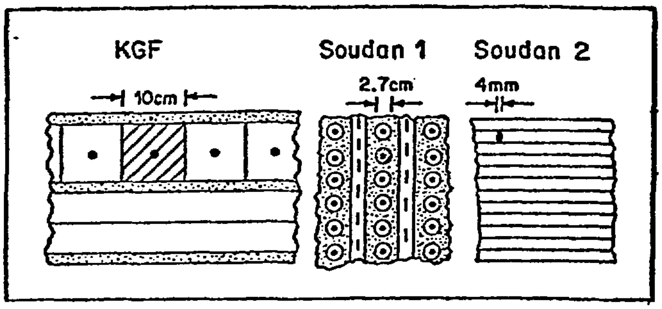

Figure 18. A comparison of the single hit resolution of the Kolar apparatus, Soudan I and Soudan II.

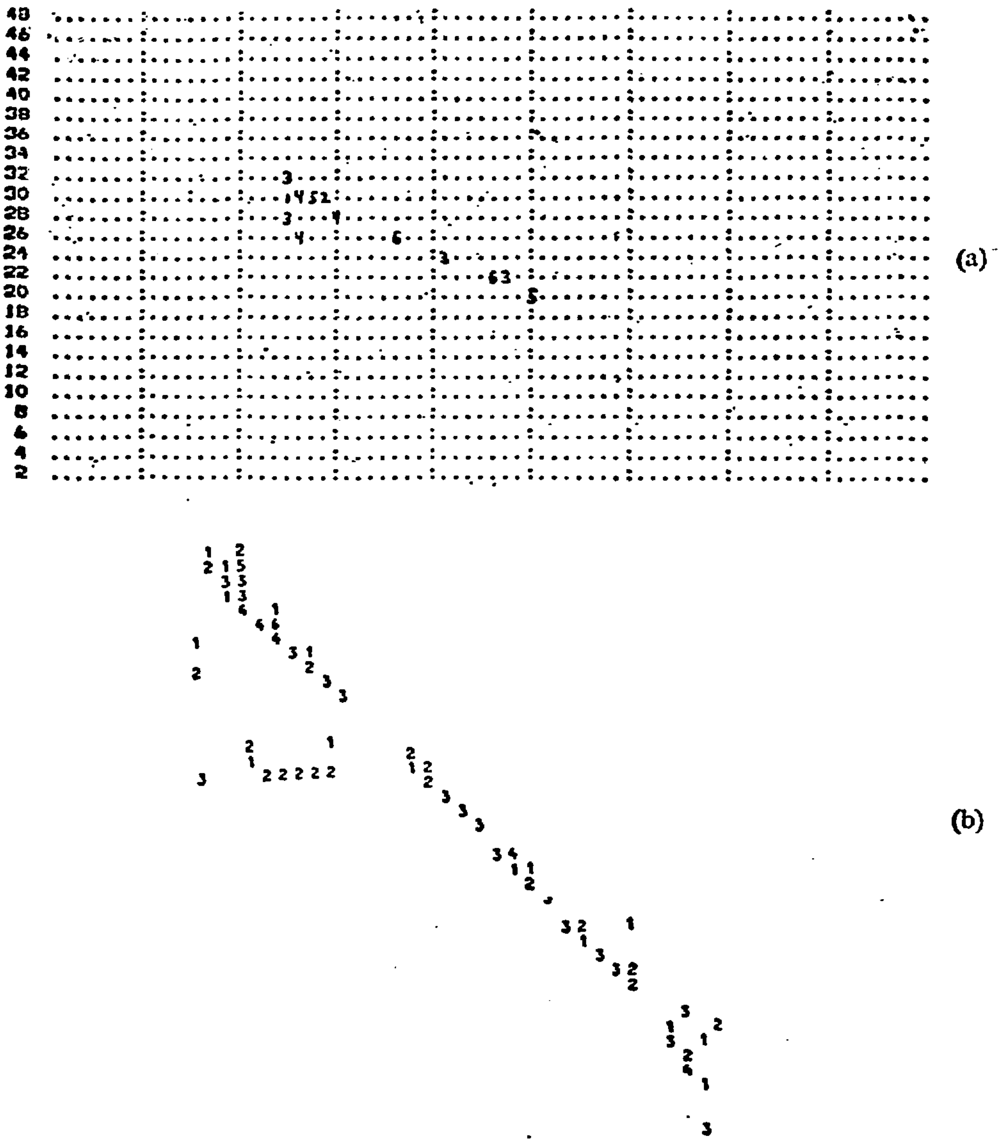

Figure 19. One view of a Monte-Carlo $p \to e^+ \pi^0$ decay. (a) As would be observed with Soudan I. (b) As would be observed with Soudan II.

5. Soudan II

To build Soudan II, the Minnesota and Argonne groups have been joined by Oxford. The Soudan II group is now H. Courant, K. Heller, S. Heppelmann, T. Joyce, M. Marshak, E. Peterson, K. Ruddick, M. Shupe from the University of Minnesota, D. Ayres, K. Coover, J. Dawson, T. Fields, N. Hill, D. Jankowski, E. May, L. Price from Argonne National Laboratory and W. Allison, C. Brooks, J. Cobb, D. Perkins, and B. Saitta from Oxford University. This detector is described in detail elsewhere (Bartelt *et al* 1981). Soudan II will be a 1000-ton tracking ionization calorimeter consisting of iron plates and drift modules. For comparison the resolutions of the Kolar detector, Soudan I and Soudan II are shown in figure 18. Figure 19 shows a Monte-Carlo generated event, $p \rightarrow e^+ \pi^0$ in Soudan I and the same event with the much finer resolution of Soudan II. In addition to the bubble chamber quality of the Soudan II event pictures, directionality and particle identification can be reliably achieved from the track geometry and ionization. We hope to begin construction of Soudan II by the beginning of 1983.

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