ANL-HEP-CP--82-17

DE83 010741

ANL-HEP-CP-82-17

Conf-820466--3

PLANNING FOR THE NEXT GENERATION OF PROTON-DECAY EXPERIMENTS IN THE UNITED STATES*

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Abstract

There are now three well-developed proposals for new proton-decay detectors to be built in the United States. These are the 1000-5000-ton Soudan 2 tracking calorimeter, the 1400-ton Homestake II liquid scintillator Tracking Spectrometer, and the 2500-ton University of Pennsylvania liquid-scintillator - proportional-drift-cell calorimeter. These proposals were reviewed by the Department of Energy Technical Assessment Panel on Proton Decay in February 1982. I shall describe the Soudan and Pennsylvania proposals, present the latest results from the 31-ton Soudan 1 experiment, and discuss the recommendations of the DOE Panel. Following these recommendations, a one-week workshop, to be held at Argonne in June, will focus on the optimization of techniques for future experiments.

1. Introduction

In February 1982 the U.S. Department of Energy Technical Assessment Panel on Proton Decay met to review the status of the U.S. proton decay experiments which are in operation or construction, and to consider proposals for new experiments. The experiments make use of three general techniques, each with special capabilities and limitations: the water Cerenkov detectors, the fine-grained sampling calorimeters (typically built of iron and track chambers), and the

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*Talk presented at the Third Workshop on Grand Unification, Chapel Hill, North Carolina, 15-17 April 1982.

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totally active calorimeters (typically using liquid scintillator). Ideas for more advanced detectors were also presented: the liquid-argon drift calorimeter by the HPW collaboration, and the R&D program at Berkeley on a very high pressure argon time projection chamber.

In its recommendations [1], the panel advised that no new experiments be approved but that the situation be reviewed after a year, when results might be known from the water Cerenkov detectors and when R&D work in support of the calorimeter proposals would be completed. The panel also suggested that a workshop be held soon to discuss the optimum design and deployment of the next U.S. experiment. This workshop will be held at Argonne National Laboratory in June. Finally, the panel suggested that a national underground laboratory should be considered, to support both proton decay experiments and other underground physics research. A workshop on this subject will be held at Los Alamos National Laboratory in September.

I shall review the two proposals for new experiments which were presented to the panel and have not already been described at this meeting (Soudan 2 and the Penn Design Study), and also present the latest results from the Soudan 1 experiment. A synopsis of the issues to be resolved for the U.S. program is presented in the last section.

2. Results from Soudan 1

The Soudan nucleon decay program [2-6] is being carried out in the Soudan iron mine in northeastern Minnesota, at a depth of 2000 m of water equivalent. A 31-ton prototype experiment, Soudan 1, has been built and is now being operated by a University of Minnesota - Argonne National Laboratory collaboration. The Soudan 1 detector consists of a 3 m × 3 m × 2 m block of taconite(iron ore)-loaded concrete, which is instrumented with 3456 gas proportional tubes in a crossed array, and has an average density of 1.85 g/cm^3. The detector began routine data acquisition in August 1981; turnon of the scintillation-counter active shield in October 1981 made the experiment fully operational. This shield surrounds the detector on the top and four sides, and signals the presence of charged particles from cosmic-ray interactions in the rock around the experiment. Such events can produce low-energy neutrals which resemble nucleon decays when they interact in the detector. Soudan 1 is providing valuable data on the rates and characteristics of such events, which are a potential source of background to nucleon decay in the proposed Soudan 2 experiment.

Preliminary analysis has now been completed on a total of 63 days of data from Soudan 1, yielding the following sample of events:

190,000	cosmic-ray muon events
1,100	multiple parallel muon events ($2 < N_\mu < 12$)
395	stopping muons (0.21% of the total)
70	observed μ^+ decays (giving 35±4% detection efficiency)
1	upgoing muon candidate (from a ν + rock interaction?)
0	neutrino interactions in the detector (~ 0.5 expected)
0	nucleon decay candidates
0	slow magnetic monopole candidates

Events with multiple parallel muon tracks can yield information on the nuclear composition of the very high energy cosmic-ray primaries which interact in the upper atmosphere to produce bundles of decay muons. Figure 1 shows the multiplicity distribution of these events. In addition, the very high-energy muons which traverse the detector occasionally produce spectacular interactions, demonstrating the excellent pattern-recognition capabilities of Soudan 1. An example is shown in Figure 2.

The lack of nucleon decay candidates gives the lower limits on the nucleon lifetime listed below. The fiducial-mass values are from Monte-Carlo event-containment studies, using the same cuts which were applied to the data. The detection efficiencies include a nuclear absorption loss of 20% per pion in the parent nucleus (a remaining e^+ is seen with 50% efficiency), and the > 8-tube cut on the number of hit proportional tubes.

Decay mode	Fiducial mass	Detection efficiency	τ/branching ratio (90% C.L.)
$p \to e^+\pi^0$	11 tons	90%	4.5×10^{29} years
$n \to e^+\pi^-$	13 tons	90%	5.4×10^{29} years
$n \to \mu^+\pi^-$	11 tons	90%	4.5×10^{29} years
$p \to \nu\pi^+$	16 tons	70%	5.2×10^{29} years
$n \to \nu\pi^0$	15 tons	80%	5.5×10^{29} years
$p \to \nu K^+$	16 tons	35%	2.6×10^{29} years

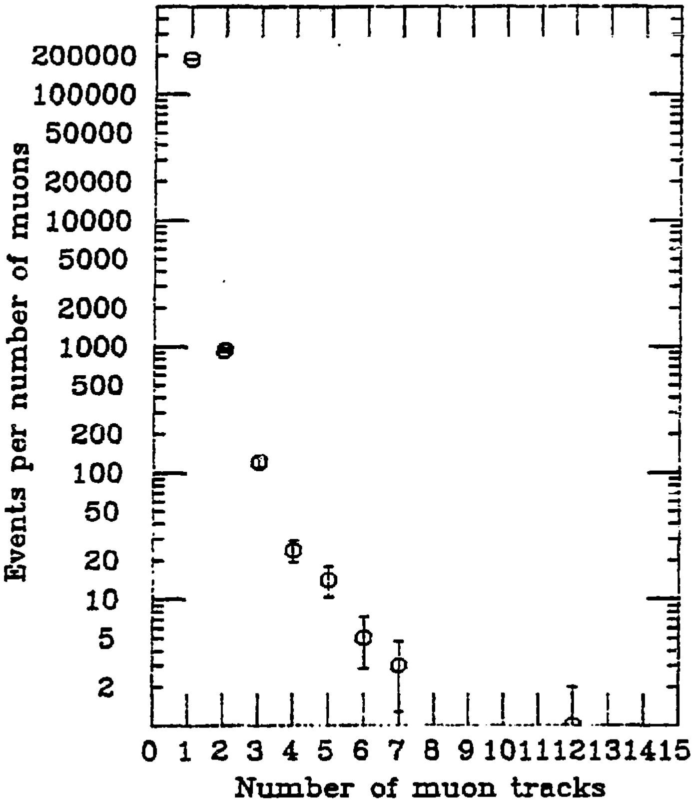

Figure 1. Muon multiplicity distribution from Soudan 1 for single muons and for events with two or more parallel tracks.

The scintillation-counter cosmic-ray veto shield has proved to be quite powerful in rejecting events induced by cosmic-ray interactions in the rock. Figure 3 shows an example of such an event, which strongly resembles a nucleon decay except for the hits in six veto counters.

A Monte-Carlo simulation has been used to calculate the Soudan 1 acceptance for slow, ultraheavy, "GUT" magnetic monopoles. The presence of these particles would be apparent in the timing data from the proportional tubes, which are sensitive for a 7 μsec period around the trigger time. For monopoles which ionize like muons, the velocity range in which Soudan 1 is sensitive is $2 \times 10^{-3} < \beta < 1.5 \times 10^{-2}$. The lack of candidates gives a 90% confidence-level lower limit on the monopole flux of $2.2 \times 10^{-5}/\mathrm{cm}^2$ sr yr. This result is compared below

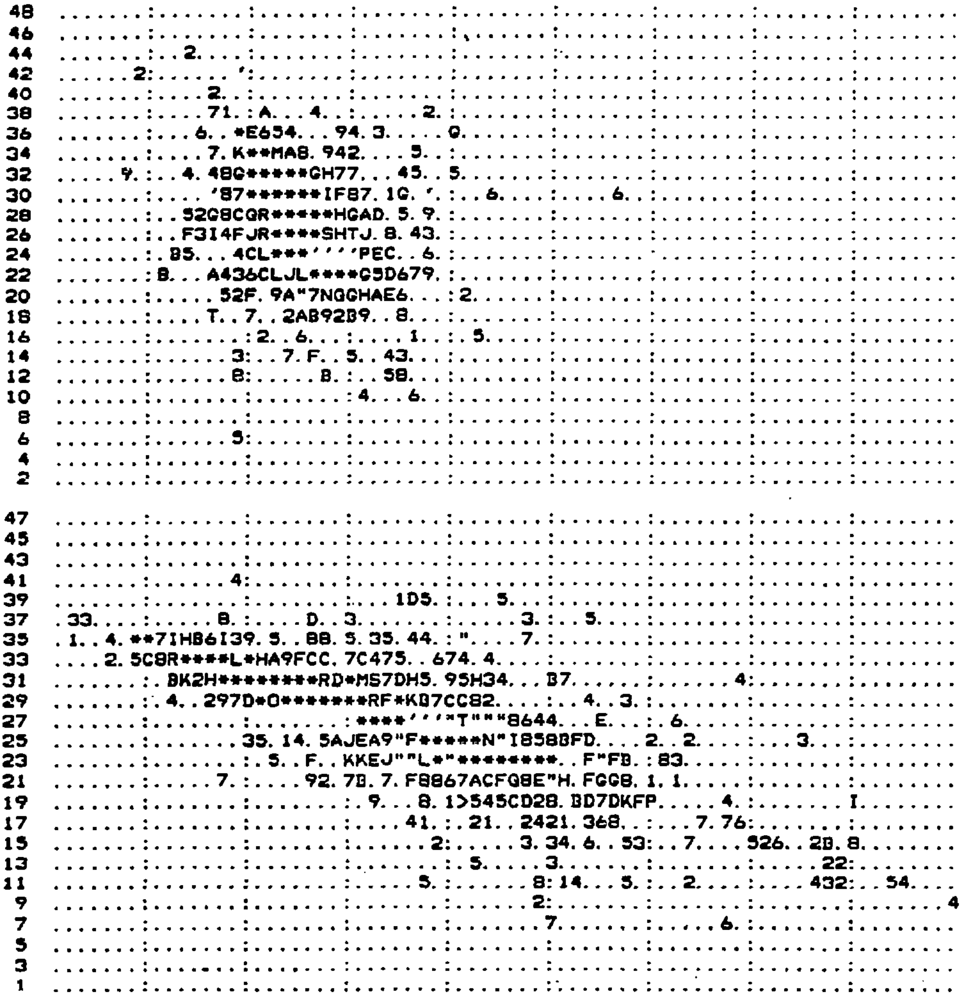

Figure 2. Two views of a fully contained electromagnetic shower in the Soudan 1 detector. In the lower (north-south) view, the incident muon enters from the top left and exits at the bottom right. The total shower energy is roughly 200 GeV. Numbers, letters and asterisks indicate observed pulse height, where pulse height increases as 1,2,...9,A,...,Z,*.

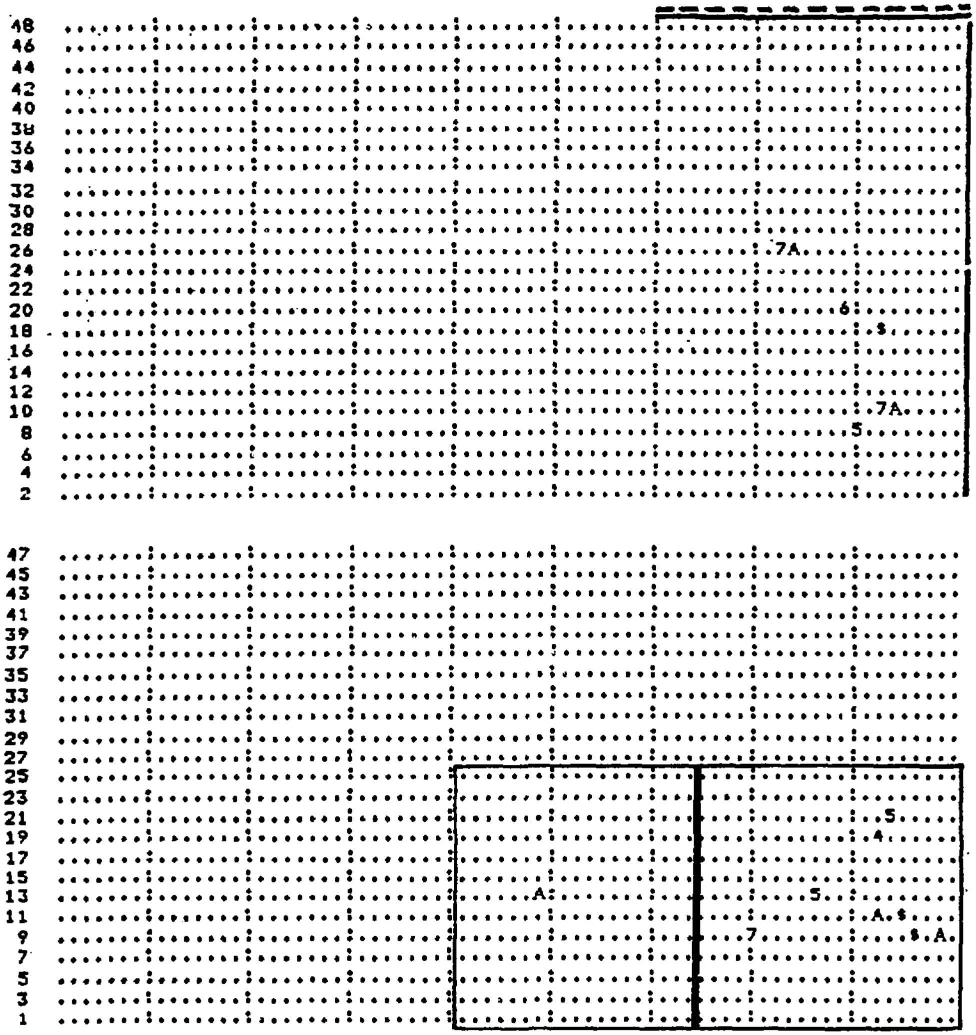

Figure 3. Two views of a nucleon decay background event in the Soudan 1 detector. Numbers, letters, and dollar signs show proportional tubes which were hit. This event is clearly identified as being due to a cosmic-ray interaction in the nearby rock by the six veto counters (indicated by lines and rectangles) which were hit.

with some other recent limits on the flux of GUT monopoles. Not shown here are even more restrictive bounds from the Kolar Gold Fields experiment and from the Baksan Underground Scintillation Telescope, which I understand will become available in the near future [7]. It seems clear that, if the monopole candidate recorded by Cabrera [8] is real, these particles ionize much less than relativistic light particles, are generally slower than $\beta = 10^{-3}$, or will soon be detected by other methods.

Experiment	Flux ($m^{-2}sr^{-1}day^{-1}$)	dE/dx cut (I_{min} units)	β Range	Method
B. Cabrera [8]	<0.5	none	any	superconducting loop
J. Ullman [9]	<0.05	>2	3×10^{-4} to 1.2×10^{-3}	proportional tubes
R. Bonarelli, *et al.* [10]	<0.002	>25	7×10^{-3} to 0.6	scintillation counters
Soudan 1 (preliminary)	<0.0006	>0.3	2×10^{-3} to 1.5×10^{-2}	proportional tubes in deep mine

A 700-lb facsimile of the Soudan 1 detector has been exposed to low energy $\pi^\pm$, $\mu^\pm$, and $e^\pm$ in a test beam at the Argonne Rapid Cycling Synchrotron. The results have been compared to predictions of the Monte-Carlo simulation of the detector and the agreement is excellent. Figure 4 shows the average number of hit tubes for negative particles as a function of beam momentum.

3. The Soudan 2 Proposal

The Soudan 2 proposal [4] to build a 1000-ton tracking calorimeter detector was submitted to the U.S. Department of Energy and the U.K. Science and Engineering Research Council in September 1981 by the Minnesota-Argonne-Oxford University collaboration. Recently, the collaboration has suggested that the detector be made expandable, by installing it in an underground cavity large enough for

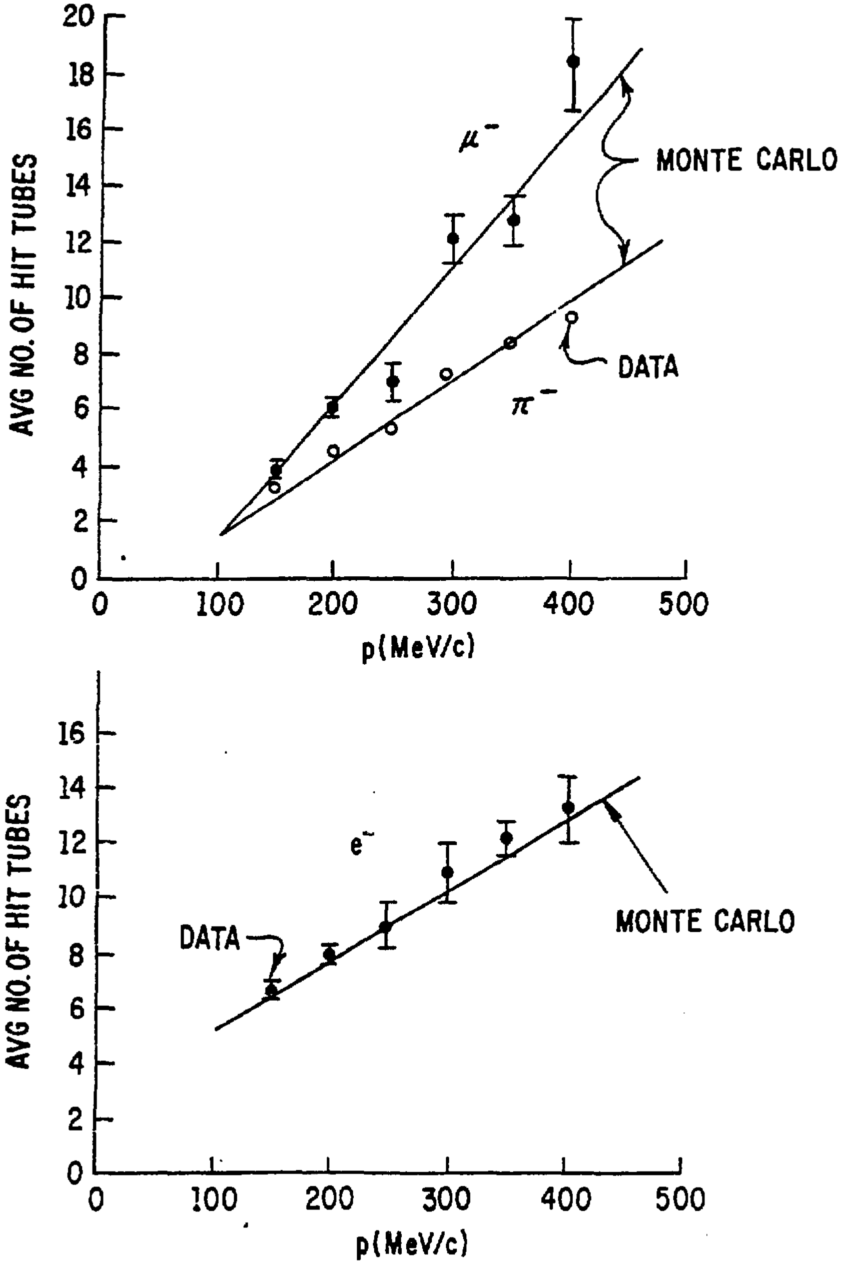

Figure 4. Comparison of Soudan 1 test-beam data and Monte-Carlo predictions. The average number of hit proportional tubes is shown as a function of beam momentum for π^-, μ^-, and e^-.

an eventual 5000 ton experiment, which would be built after experience was gained with the initial 1000 tons. The 1000-ton Soudan 2 could be operating in 1985, and the 5000-ton expansion in 1987.

Soudan 2 achieves fine-grained ionization sampling and tracking at a reasonable cost by drifting ionization in long gas channels within the iron calorimeter material. The ionization is detected by planes of crossed proportional wires and cathode strips on the 5 m × 5 m faces of 50-ton movable modules. Planar drift-chambers with 50 cm drift distances have been developed to implement this idea [6]. Figure 5 shows schematically how the detector would be assembled from such chambers. Development work is continuing on schemes which use drifting in 1 to 2 cm diameter cylindrical columns to achieve more isotropic ionization sampling.

The Soudan 2 detector is characterized by excellent spatial resolution and pattern-recognition ability. Its bubble-chamber-like "pictures" of events provide a powerful tool for dealing with unexpected background processes or unexpected physics. For $p \rightarrow e^+\pi^\circ$ decays, the detector records typically 60 drift-chamber-cell hits, and achieves an energy resolution σ_E/E of about 20%. Since μ^- are captured in the iron and do not decay visibly, the observation of μ^+ decays gives the ability to determine muon charge. Detection of $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ gives similar capability for $\pi^\pm$ charge determination. As for most dense detectors, Soudan 2 has excellent event-containment properties, which allow the detailed study of small modules in accelerator test beams.

Sensitivity to three-prong nucleon decay modes in Soudan 2 averages 64% after cuts to reject background events. Using only the three-prong modes, and SU(5) branching ratios, the 1000-ton experiment would identify about one decay per year (after cuts) if the nucleon lifetime were 10^{32} years. Monte-Carlo studies have recently shown how to use the measurements of ionization along particle trajectories to determine the direction of particle motion. Uncertainty on this point had previously prevented the calculation of sensitivity to two-prong nucleon decay modes which, in the absence of directionality information, are topologically very similar cosmic-ray neutrino interactions. Test-beam data from the Soudan 1 facsimile module have been used to confirm the Monte-Carlo predictions. Figure 6 shows the test-beam results for 300 MeV/c μ^- tracks, 84% of which deposit more

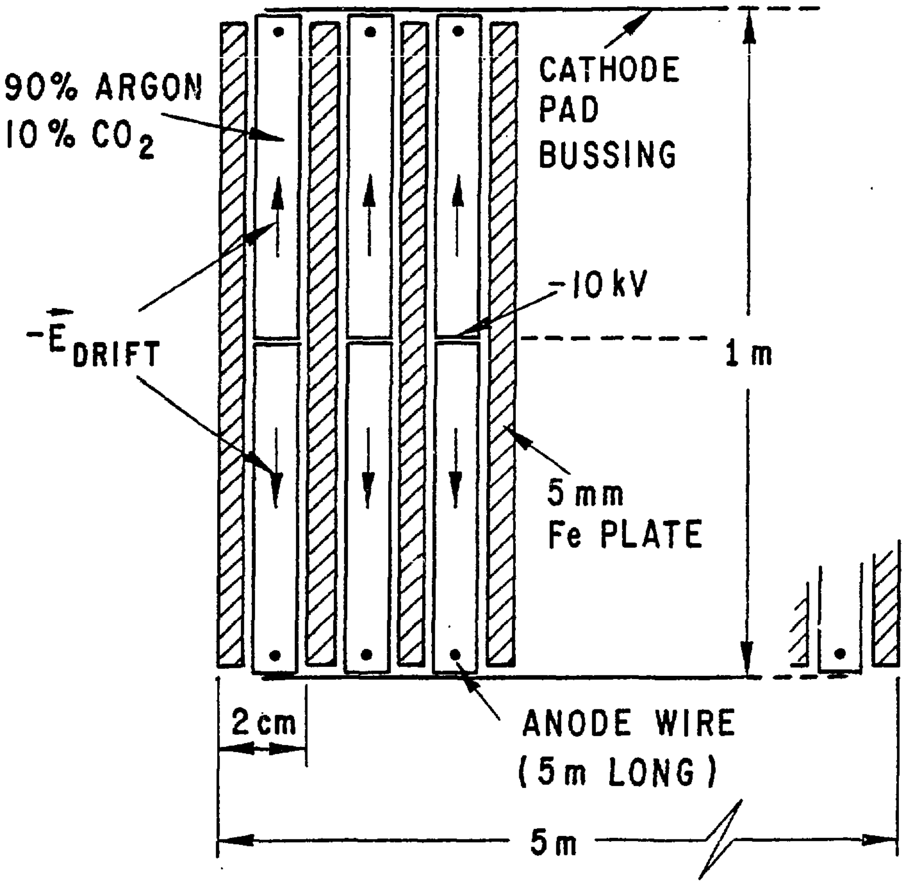

Figure 5. Schematic representation of the construction of a 50-ton Soudan 2 module from 5-mm thick iron plates and 5 m × 0.5 m × 1 cm planar drift chambers. Note that the horizontal and vertical scales are different. The module contains 500 chambers and is read out by 500 anode wires and 500 cathode strips on the two external 5 m × 5 m faces. The average density is 2 g/cm^3.

ionization in the last third of their tracks than in the first third. For 300 MeV/c π^-, the direction of motion is correctly determined for 72% of the tracks. The finer sampling in Soudan 2 gives particle direction for an even greater fraction of the tracks.

Monte-Carlo calculations show that neutrino-induced backgrounds to three-prong nucleon-decay modes is < 0.5 event/year in Soudan 2. Backgrounds from cosmic-ray induced interactions in the surrounding rock are expected to be < 0.1 event/year. Since this rate is already substantially less than the neutrino background rate, little would be gained by going deeper than the proposed depth of 2000 m of water

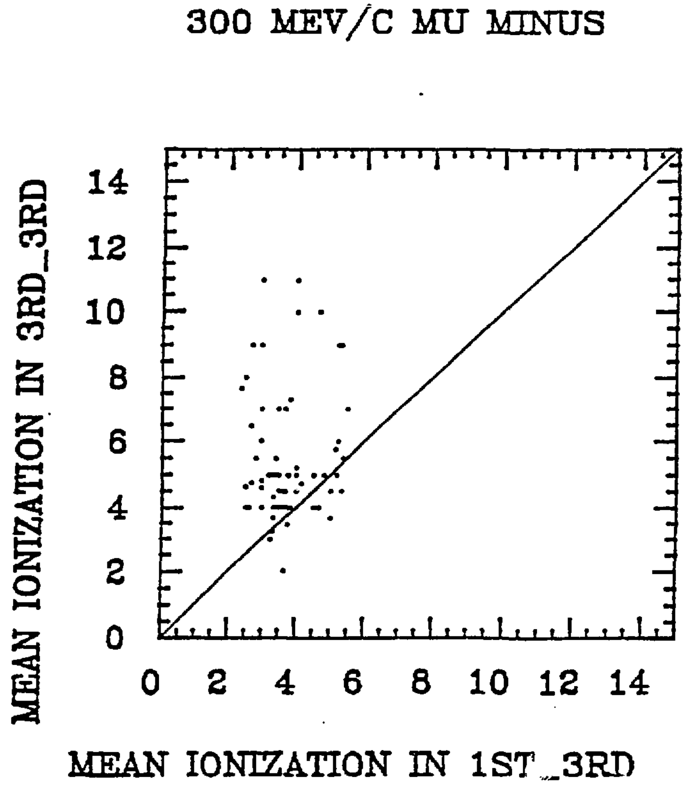

Figure 6. Test-beam data from the Soudan 1 700-lb facsimile module. The data show that the direction of motion of 84% of 300 MeV/c μ^- can be determined by comparing the ionization deposited in the first third and the last third of the tracks. Monte-Carlo simulations predict even better directionality determination in Soudan 2.

equivalent. Continuing Monte-Carlo studies are aimed at optimizing background rejection in Soudan 2 before the calorimeter design is finalized later this year.

4. The Penn Design Study

The proposal to build the 2500-ton Penn Nucleon Decay Detector [11,12] was submitted to the Department of Energy in the fall of 1981 as a design study by a group from the University of Pennsylvania. The detector is a totally active calorimeter based on liquid scintillator, and incorporates fine-grained tracking with spatial resolution similar to that of Soudan 2. The proposed design

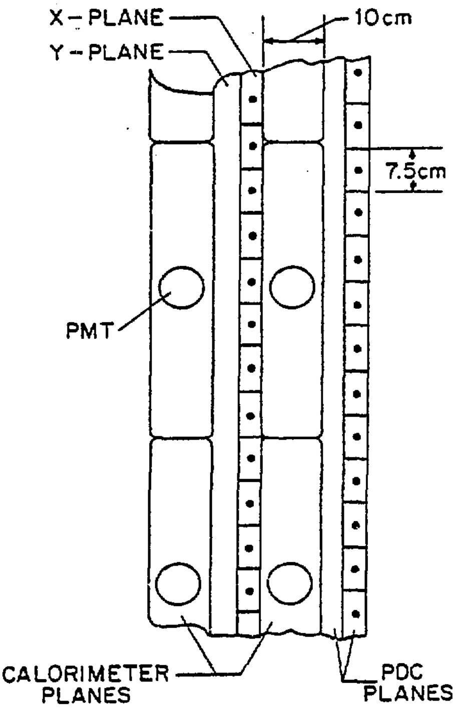

Figure 7. Schematic outline of a double module of the Penn Nucleon Decay Detector (from Ref. 12). The ends of two 8-m long liquid scintillator calorimeter planes are shown, along with the crossed planes of proportional drift cells (PDC's).

is an extrapolation of a 170-ton detector for 1 GeV neutrino interactions, which is now in operation at the Brookhaven AGS [13]. Many of the properties of the nucleon decay detector can be measured directly from this "prototype". The proponents suggest that the detector be built at the recently proposed National Underground Physics Laboratory [14,15], although a definite site has not yet been selected. The experiment could be ready to operate in 1985.

Figure 7 shows a cross section of the calorimeter construction. It utilizes 6700 liquid scintillator cells, each 10 cm × 50 cm × 8 m and viewed by photomultiplier tubes at both ends. Between the planes of scintillator cells are two crossed planes of proportional drift cells, to give two high-resolution views of each event. The assembled detector would be 8 m × 8 m × 61 m and would have an average density of 0.64 g/cm^3. It contains 84,000 drift cells and 13,400 3-inch photomultipliers. Construction techniques and costs are already well understood from the Brookhaven detector experience. A $p \to e^+\pi^0$ decay would produce about 60 drift-cell hits in the detector and would be characterized by an energy resolution $\sigma_E/E \sim 10\%$. The Penn detector determines the charge of stopping pions and kaons by observing the nuclear stars produced by stopping negative hadrons and the decay products of stopping positive mesons. Energy-loss data from the liquid scintillator will give this calorimeter excellent particle-identification capabilities. Muon decay and muon polarization are easily detectable in liquid scintillator, but muon charge must be inferred from the charges of accompanying hadron decay products. The rejection of cosmic-ray-induced backgrounds is improved by timing information ($\sigma_t \sim 2$ nsec), which allows the direction of motion of most particles to be determined.

5. Issues to be Resolved for the U.S. Program

The recommendations of the DOE Technical Assessment Panel on Proton Decay reflect a disagreement among researchers on a number of issues which are essentially technical. Such uncertainties are inevitable when experiments of unprecedented size and sensitivity are proposed to search for a rare process with unknown characteristics in an environment where the important backgrounds have not yet been measured experimentally. The questions which must be resolved before the U.S. program can proceed will be discussed in depth at the workshop at Argonne this summer. A synopsis of the most important issues is given here:

(1) When should the next generation of experiments begin?

Some argue that nothing should be decided until we have results from the water Cerenkovs: if these experiments work well and do not see decays, then the technique should be extended to larger masses; if a signal is seen, we will know much better what kind of device to build to study proton decay in detail. Others argue that the physics importance of <u>any</u> result, positive or negative, will require it to be verified by techniques which are as different as possible from the water Cerenkovs. Both the decay modes and the backgrounds are unknown, and experimental sensitivity and background rejection depend on the actual decay modes and on the detection technique. Finally, the experiments are large and difficult. It may be several years before we learn the real capabilities of the water Cerenkovs, and it will certainly take years to bring any new experiment into operation. If we want to know the answer in this decade, we'd better get started!

(2) What is the optimum balance between mass and background rejection?

The ultimate sensitivity of any experimental technique depends on both the total mass monitored for decays and on the ability of the detector to reject background. The largest detector will not necessarily be the most sensitive.

(3) At what depth should the next large detector be built?

Existing sites deeper than 2000 m of water equivalent are rare in the U.S. Excavating a new, deep site costs money which might better be spent on detectors. If cosmic-ray muon induced backgrounds at modest depths can be easily reduced well below the level of the depth-independent neutrino backgrounds (as claimed in the IMB, HPW, and Soudan proposals), then excavating deeper laboratories is unnecessary.

(4) What type of detector should be built next?

Three techniques have been extensively developed: water Cerenkovs, fine-grained sampling calorimeters, and totally active calorimeters. The water Cerenkovs provide the largest mass per dollar, but their relatively poor pattern recognition for complex topologies may limit background rejection capability. Sampling calorimeters can have excellent pattern recognition ability, and if ionization is measured they can usually determine the direction of a particle's motion, perhaps as well as detectors which measure time of flight. All techniques have some particle-identification capability, but there are significant differences. Water Cerenkovs cannot measure the charge of stopping tracks but can measure muon polarization; iron calorimeters can often measure muon and hadron charges but not muon polarization. Liquid scintillator detectors can usually determine hadron charges and muon polarization, and their potentially excellent energy resolution can be combined with track-chamber pattern recognition to give them the best background rejection for two-body decay modes with neutrinos. In general, the more information produced for each event, the greater the cost per ton of detector.

(5) What is the real cost of detectors, normalized for sensitivity?

In addition to the cost per ton of instrumented detector, the fiducial-to-total-mass ratio and decay detection efficiency must be taken into account. For decay modes with electrons and photons, iron calorimeters can have much higher fiducial-mass fractions than water or scintillator detectors. However, this gain is partially offset by the higher losses due to nuclear absorption of pions in iron, and is complicated by the greater "crosstalk" between channels with pions. Uncertainties about actual fabrication costs (as opposed to estimates), and the practicality and reliability of different types of experiments in the underground environment can be resolved by careful engineering and by the operation of large prototype detectors.

(6) How important is other underground physics likely to be?

The proton decay detectors themselves have varying capabilities for the study of other physics topics, for example cosmic-ray neutrinos and muons, and monopole searches. Other important experiments also require underground laboratories (for example solar neutrino experiments), and perhaps construction costs should be shared among several efforts in addition to proton decay, for both practical and physics benefits. Some have speculated that the real discoveries which will result from the search for proton decay will be very different from anything we now imagine. Moreover, grand unified theories now suggest that the most fundamental experiments in particle physics may require underground facilities on the scale of those now provided at the accelerator laboratories. If these predictions prove to be correct, the notion of a national underground physics laboratory may be an idea whose time has come.

Acknowledgements

It is a pleasure to thank my colleagues on the Soudan experiments for their hard work in obtaining and understanding the results presented here. My insight into the interplay of physics and instrumentation issues in the search for proton decay has benefited from spirited discussions with the proponents of other experiments. This work was supported in part by the U.S. Department of Energy and the U.K. Science and Engineering Research Council.

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