A Tribute to Dave Ayres: The Soudan 1 Detector

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Proton Decay

- By 1978, unification-mania was rampant in the particle physics community
- The observation of neutrino neutral current interactions supported electroweak unification
- CERN was enthusiastically working towards the discovery of the W and Z
- Theorists were one step ahead, developing GUT models to unify strong, EM and weak interactions
- Most popular GUT model (SU5) predicted observable proton decay with a lifetime of $\sim 10^{30}$ years

Proton Decay

- U.S. physicists formed one, and later two, collaborations to search for proton decay.
- IMB (Irvine-Michigan-Brookhaven) worked towards an 8 kT water Cerenkov detector in the Morton Salt Mine in Fairport Harbor, Ohio, where Fred Reines had done previous experiments while at Case.
- HMPW (Harvard-Minnesota-Purdue-Wisconsin) planned to build a ~1 kT detector cheaper and faster, but where?
- Eventually, HMPW chose the Soudan Mine in northeastern Minnesota.

Proton Decay

NEWS

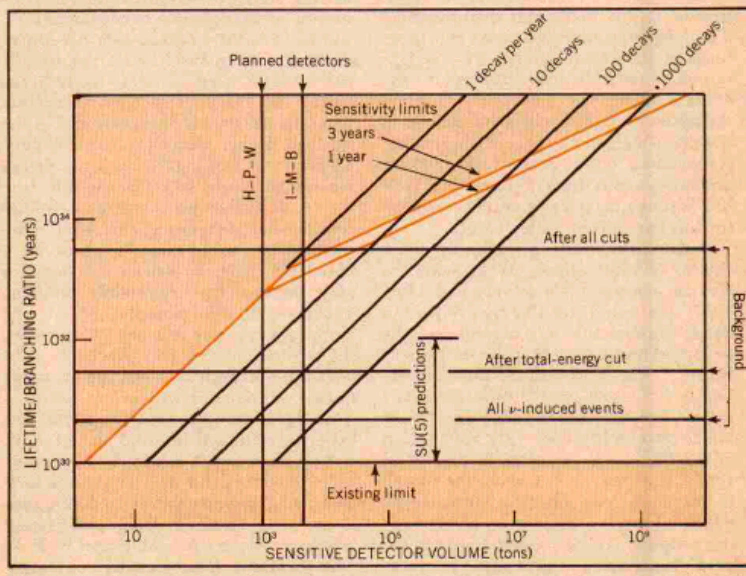
Physics Today, January 1980

search & discovery

Underground experiments will look for proton decay

Although we know of no symmetry in nature that requires the conservation of baryon number, the stability of ordinary matter would appear to attest to the absolute stability of the proton. But we're soon to have a closer look. Two groups of high-energy physicists are preparing to descend into mines in Ohio and Utah, to look for proton decays with detectors several orders of magnitude more sensitive than any employed for such a search in the past.

The present experimental lower limit on the lifetime of the proton, about 10^{30} years,[1] is "tantalizingly close" to the current consensus of theoretical estimates, says David Cline, spokesman for the Harvard–Purdue–Wisconsin group that is planning to set up its detector in a Utah silver mine. In the past year or so, detailed calculations based on the leading candidates among the "grand unification" schemes for elementary particles have been yielding ever lower estimates of the proton lifetime, apparently converging now around 10^{31} years[2], plus or minus a couple of orders of magnitude. The larger of the two detectors, the 10-kiloton Irvine–Michigan–Brookhaven detector planned for a salt mine on the shores of Lake Erie, is expected to be sensitive to proton lifetimes as long as 10^{33} years. Both experiments have recently been



Proton-decay signal and background rates for large water-Cerenkov detectors, as a function of proton lifetime and detector volume. Black diagonals are lines of constant decay rate. Horizontal lines indicate cosmic-ray neutrino-induced background with various levels of background discrimination. Colored diagonals show sensitivity limits for one and three years of observation. When background becomes comparable to signal, sensitivity grows only as square root of volume. Vertical lines indicate large water-Cerenkov detectors planned by the I-M-B and H-P-W collaborations.

Soudan Mine

- Although HMPW submitted a proposal to DOE, some people were nervous about Soudan—too cold, too remote, not "theirs"
- HPW moved to the Silver King Mine in Park City Utah. "M" looked for new collaborators. Dave Ayres, John Dawson, Tom Fields, Ed May and Larry Price joined the experiment. Keith Ruddick proposed a new design—proportional tubes and concrete loaded with magnetite concentrate.

Soudan 1 Detector

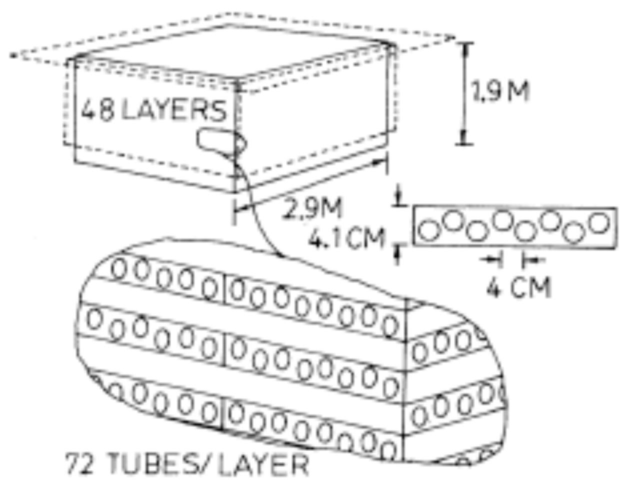
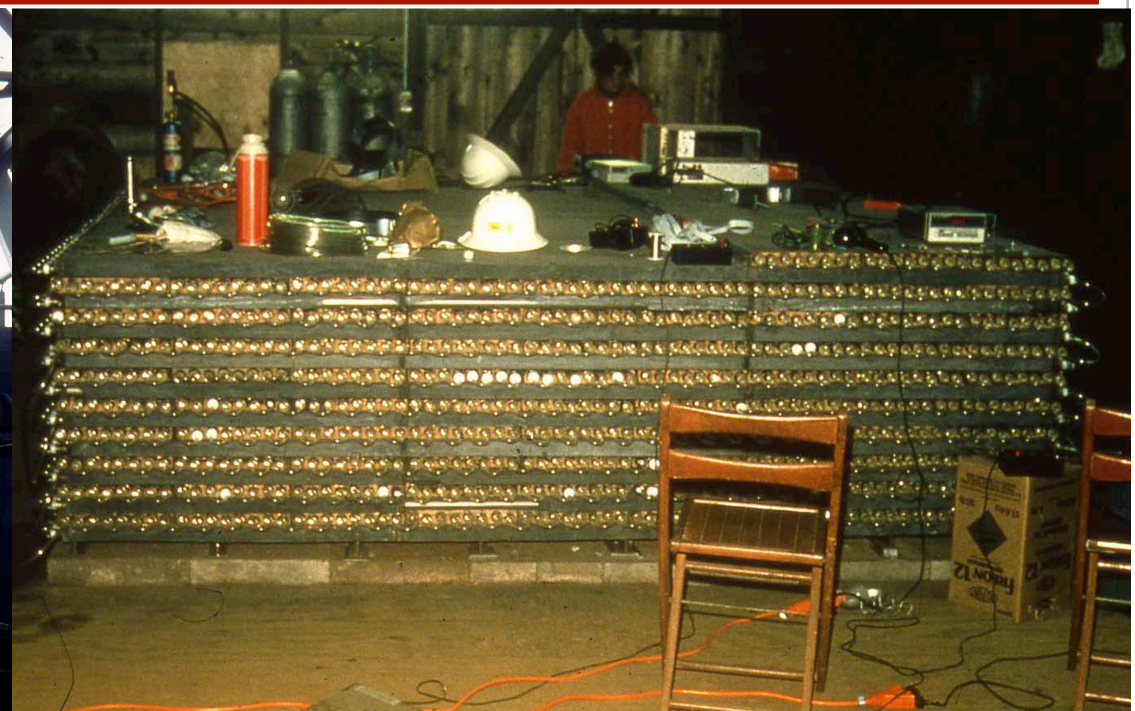
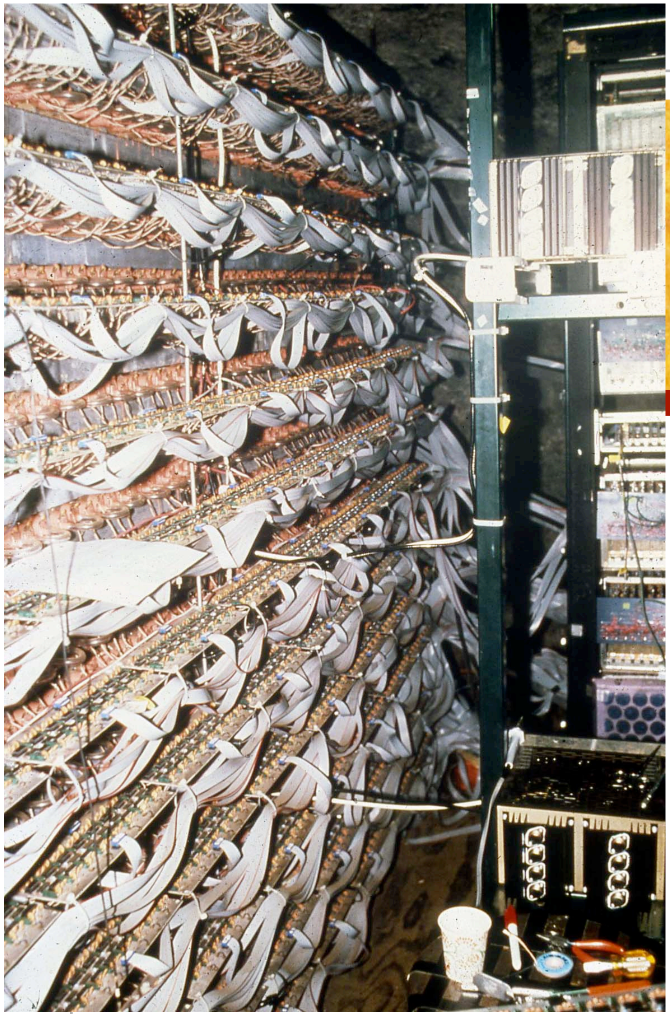


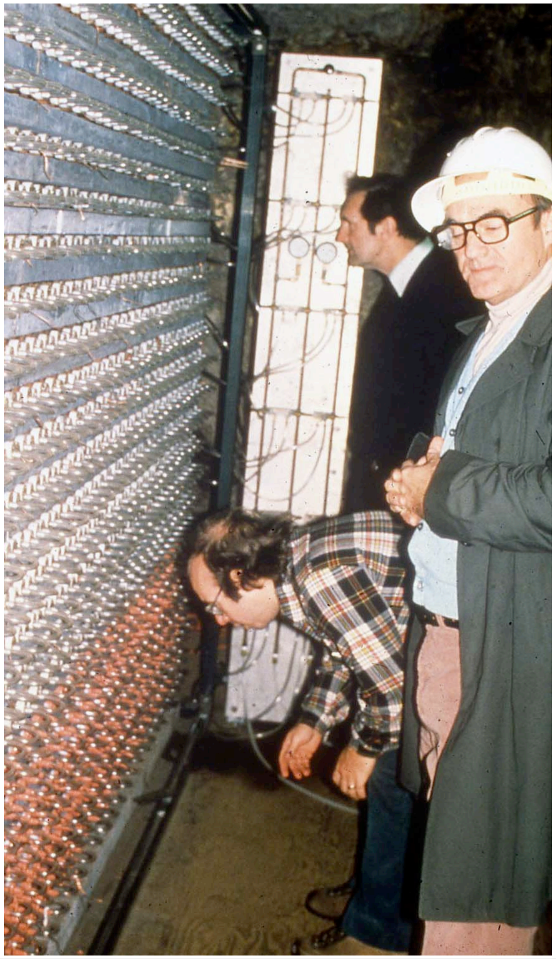
FIG. 1. A schematic view of the Soudan-1 detector.

Soudan 1 Detector



Soudan 1 Detector





Soudan 1 Proton Decay Search

Results from a New Search for Proton Decay

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(Received 5 November 1982)

The authors have searched for the decay of protons and neutrons bound in nuclei using Soudan 1, a 31.5-metric-ton iron-loaded concrete tracking calorimeter, instrumented with 3456 proportional tubes. During a live time of 0.38 yr, the authors have observed one candidate event wholly contained within the detector. If this event is attributed to a background source, a lower bound (90% confidence level) can be established on the lifetime for nucleon decay through any of a wide range of modes of 1×10^{30} yr.

PACS numbers: 13.20.Ce, 14.20.Dh

Physical Review Letters 28 Feb 1983

Soudan 1 Proton Decay Search

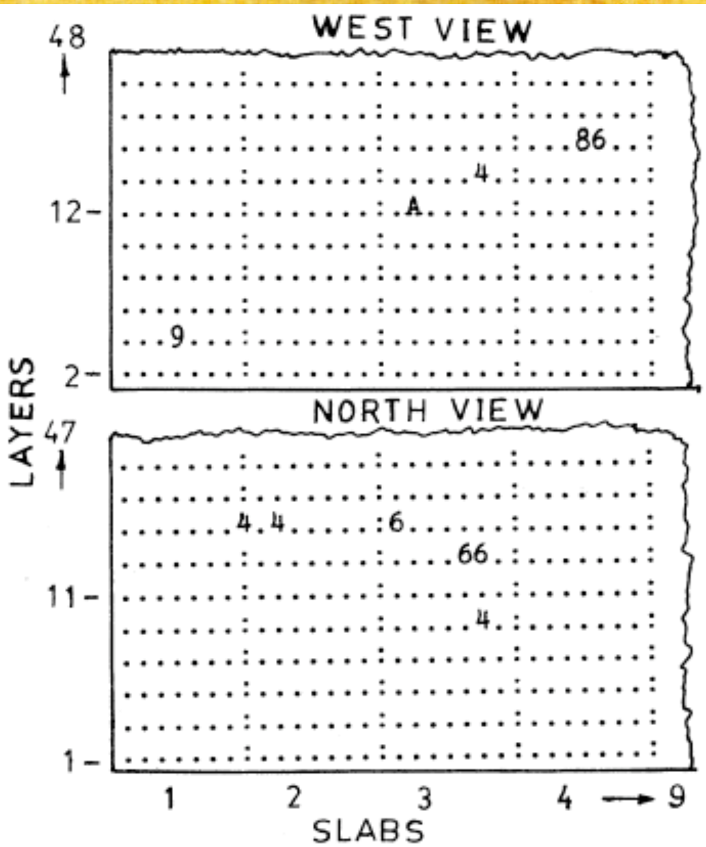

FIG. 2. Two orthogonal views of the contained event described in the text. Only the lower northwest corner of the detector is shown; the proportional tubes not shown had no outputs during this event except for one malfunctioning tube. Numbers and letters ($A=10$, $B=11$, etc.) indicate the number of time periods during which the tube output exceeded threshold and, indirectly, the ionization deposited in each tube. Minimum ionization corresponds to 3–4 time periods.

TABLE I. Detector acceptance and lifetime limits (90% confidence level) for various decay modes.

Mode	Acceptance fraction	Lifetime/(Branching ratio) (yr)
$p \to e^+\pi^0$	0.34	0.52×10^{30}
$p \to e^+\rho^0$	0.31	0.46×10^{30}
$p \to e^+\omega^0$	0.38	0.57×10^{30}
$p \to \mu^+K_s$	0.38	0.57×10^{30}
$p \to \nu K^+$	0.07	0.11×10^{30}
$n \to e^+\pi^-$	0.32	0.52×10^{30}
$n \to e^+\rho^-$	0.35	0.58×10^{30}
$n \to \nu K_s$	0.18	0.29×10^{30}
$n \to \mu^+K^-$	0.27	0.44×10^{30}

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Soudan 1 Magnetic Monopole Search

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New Limit on Magnetic Monopole Flux

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The underground Soudan-1 nucleon decay experiment can measure the velocities of slowly moving particles if they can be detected by ionization at a level 0.5 times that of a relativistic muon. Magnetic monopoles predicted by grand unified theories should satisfy this condition if their velocities are greater than $10^{-3}c$. During a live time of 0.41 yr, no candidate has been observed, implying a 90%-confidence-level limit on the flux of such objects of $<4.1\times10^{-13}$ $\mathrm{cm^{-2}\ sr^{-1}\ s^{-1}}$ for velocities between $10^{-3}c$ and $10^{-2}c$.

PACS numbers: 14.80.Hv, 94.40.Lx

Cygnus X-3

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Evidence for Muon Production by Particles from Cygnus X-3

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We have observed underground cosmic-ray muons, corresponding to a secondary flux of $\sim 7 \times 10^{-11}$ cm^{-2} s^{-1}, at a depth of 1800 m water equivalent, which appear to be initiated by Cygnus X-3. This identification is based on both direction and phase coherence. The existence of such secondary muons conflicts with the current understanding of photon cascades and/or the nature and location of Cygnus X-3.

PACS numbers: 13.60.−r, 13.85.Tp, 97.80.Jp

Cygnus X-3

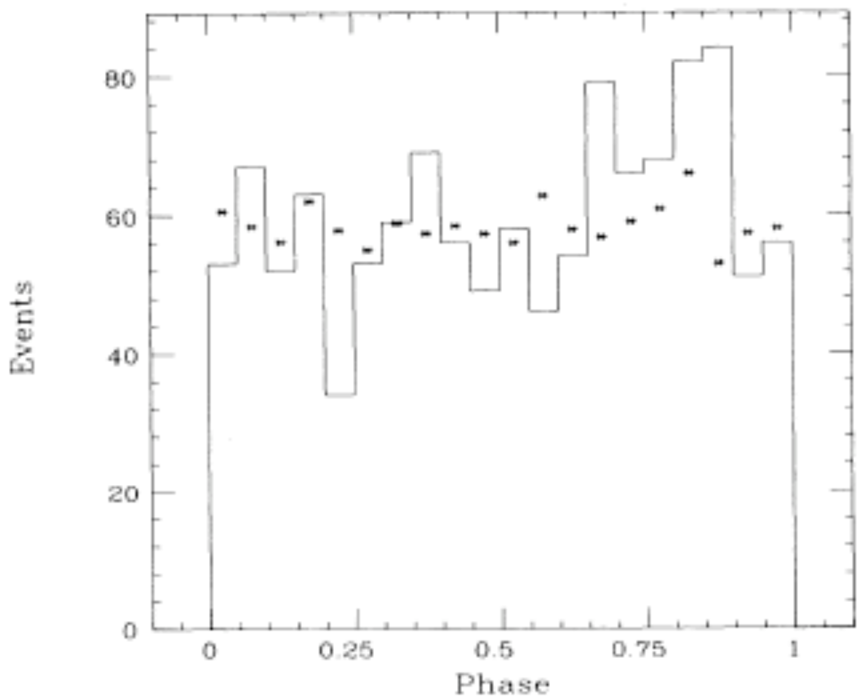

FIG. 1. Phase plot for events within 3° of the observed position of Cygnus X-3. The solid histogram shows the observed data. The points represent the expected number of events for a constant, isotropic source.

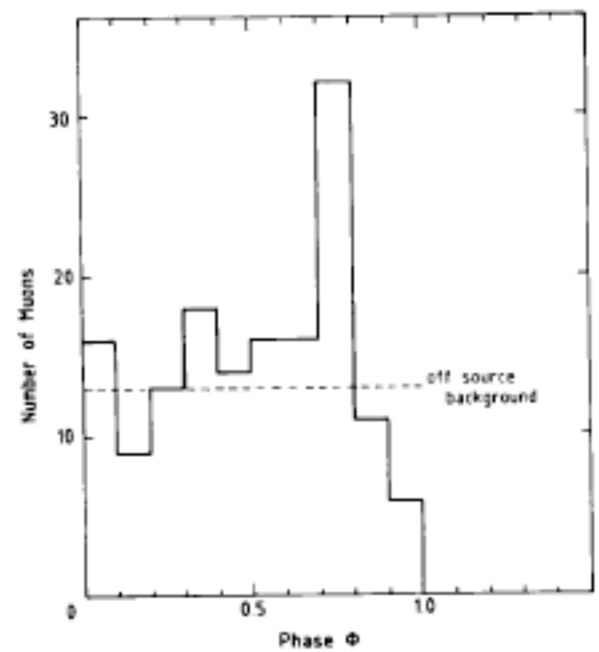

Fig. 1. Phase distribution for muons coming from an observation window of 10° × 10° centred on Cygnus X-3.

Soudan 1 Detector

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Time Distributions for Underground Muons from the Direction of Cygnus X-3

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Analysis of underground muon events from the direction of Cygnus X-3 shows evidence for large time variability of the flux in addition to the 4.8-h modulation. Our data support earlier suggestions that high fluxes occur with a 34.1-d cycle. Events measured during high-rate periods show increased statistical support for the hypothesis linking underground muons with this x-ray binary.

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Monopole-flux and proton-decay limits from the Soudan 1 detector

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Final results are presented from the search for magnetic monopoles and nucleon decay in the Soudan 1 detector, a 31.4-metric-ton tracking calorimeter located underground at a depth of 590 m. A detailed description of the detector is given. The possible existence of monopole catalysis of nucleon decay has been systematically incorporated into the analysis. During a live time of 1.0 yr, no candidates for grand-unified magnetic monopoles were observed, leading to 90%-confidence-level flux limits near 10^{-13} cm^2 sec sr.

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Coincidences between extensive air showers and the Soudan 1 underground muon detector

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We have operated the Soudan 1 underground muon detector in coincidence with a 36-m^2 detector situated at the Earth's surface. Such a combination of detectors can yield information on the composition of the primary cosmic rays at energies above $\sim 3 \times 10^{15}$ eV, where there is an abrupt change in the slope of the energy spectrum. The present experiment was meant to test the feasibility of operating such a system, and to obtain a first sample of data before the complete installation of the much larger Soudan 2 detector. These initial data seem to favor a light composition in the energy range 10^{15}–10^{16} eV, but there are significant systematic uncertainties.

PACS number(s): 96.40.De, 96.40.Pq, 96.40.Tv

Soudan 1: The Beginning

- The Soudan Laboratory started with Soudan 1.
- Despite "too cold", "too remote", the Soudan Laboratory has become a major facility for particle physics.
- Dave Ayres has made major contributions to Soudan since the beginning.
- I, personally, owe Dave enormous thanks for his cool, considered judgments through many years of ups and downs.