

haven hopes to be one of the principal centers for R&D on the Superconducting Super Collider. Samios is also pushing a multipronged program for Brookhaven particle physics: running the Alternating Gradient Synchrotron 40 weeks/year (instead of 20–30 weeks/year) for the next few years; upgrading

the AGS intensity by a factor of two to ten and using it for neutrino physics and the study of rare K decays, and possibly converting the CBA tunnel into a heavy-ion collider with greater than 15 TeV in the center of mass, provided the nuclear-physics community supports such a collider. —GBL

Proton decay not seen at predicted rate

In the year that has already seen the discovery of the three intermediate vector bosons of electroweak unification, it would be wonderful to report that proton decay has also been verified—establishing a grand unification of the weak, electromagnetic and strong interactions in one encompassing theory. But, alas, it appears we will have to be patient.

The 8-kiloton water-Cherenkov proton-decay detector built by the Irvine-Michigan-Brookhaven collaboration 2000 feet underground in a salt mine near Cleveland began operation in August 1982. With 130 full days of running now analyzed, the IMB group has not yet seen any evidence of proton decay. The most attractively simple of the grand unified theories—the “minimal SU(5)” unification proposed by Howard Georgi and Sheldon Glashow at Harvard in 1974—predicts a proton lifetime of about 2×10^{29} years, uncertain by perhaps more than two orders of magnitude. The dominant decay mode in minimal SU(5), $p \rightarrow e^+ \pi^0$, is expected to account for about 40% of all proton decays. This is in fact the decay mode to which the IMB detector is most sensitive. After 130 days, corresponding to an exposure of 4×10^{32} proton years, one would have expected to see almost a thousand $p \rightarrow e^+ \pi^0$ events if one believes the central values of the minimal SU(5) predictions.

Early IMB results indicating that minimal SU(5) was in trouble were reported by Maurice Goldhaber (Brookhaven) at the January APS meeting in New York (see PHYSICS TODAY, April, page 35.)

Before one pronounces minimal SU(5) dead, it should be noted that there is some disagreement about the theoretical uncertainties one ought to attach to these explicit predictions. Everyone, however, agrees that the uncertainty in the lifetime prediction is considerable. Although proton decay is an excruciatingly weak process, it is the computational difficulties of the strong interactions that cause the trouble. One doesn't really know how to calculate the wavefunction of the bound quark distribution in the proton. Furthermore, the key empirical parameter of the minimal SU(5) calculations, the quantum-chromodynamic

scale factor Λ , which determines the energy dependence of the strong coupling, is not well determined.

The larger the uncertainty one assigns the theoretical prediction, the less stark is the present conflict between minimal SU(5) and the IMB data. If one believes the widely accepted estimate by William Marciano (Brookhaven) that the SU(5) proton-prediction is uncertain by a factor of fifty, the prediction becomes $\tau_{e\pi} = 4.5 \times 10^{29 \pm 1.7}$ years, where $\tau_{e\pi}$ is the proton lifetime divided by the branching fraction for the $e^+ \pi^0$ mode. Taking the upper limit of this prediction, the IMB group should have seen at least eleven proton decays to $e^+ \pi^0$ during the 130 days in which they saw none. The group therefore now quotes a lower experimental limit on $\tau_{e\pi}$ of 1.0×10^{32} years at the 90% confidence level.¹ As the salt-mine detector continues running, this limit will of course increase linearly with exposure time, so long as no decays or background events indistinguishable from proton decays are seen.

The IMB water-Cherenkov detector, with a fiducial mass (the region in which proton decay vertices are sought) of 3300 metric tons of water, is by far the largest of the proton-decay detectors now in operation (see PHYSICS TODAY, January 1980, page 17). Its total sensitive water mass of 8000 tons is monitored by 2048 photomultiplier tubes arrayed just inside the surfaces of this 20-meter cube of highly purified water, looking for Cherenkov light from nucleon decay products. This arrangement is particularly well suited for the $e^+ \pi^0$ decay mode of the proton because both the positron and the two photons from the decay of π^0 would generate strong electromagnetic showers in the water, producing copious Cherenkov light. In addition to providing the Cherenkov light, the water also serves as the source of the decaying nucleons—free protons and bound protons and neutrons in the oxygen nuclei.

Two smaller detectors did in fact report tentative identifications of nucleon decay events about a year ago, quoting lifetimes and branching fractions apparently inconsistent with the present IMB limits. But since that

time, neither the Kolar gold-mine detector in India nor the Italian-CERN detector in a tunnel under Mont Blanc have found any new decay events.

Decay to $\mu^+ K^0$. The candidate event that excited the greatest interest was an apparent $p \rightarrow \mu^+ K^0$ decay recorded shortly after the Mont Blanc detector began running last year.² Both the Mont Blanc and Kolar detectors consist of layers of iron interleaved with track-recording layers of gas tubes. The Mont Blanc candidate appears to have three fully contained, charged tracks emerging from a vertex in the detector—presumably the μ^+ and a pair of charged pions from the decay of a short-lived K^0 . The measured track momenta are consistent with the decay of a proton in an iron nucleus to $\mu^+ K^0$. However, because two of the tracks run almost parallel to the layers (the direction of poorest resolution in these anisotropic detectors), the recorded event is also consistent with the collision of a cosmic-ray neutrino with a neutron (in an iron nucleus), producing only two charged tracks.

Another problem with believing the Mont Blanc $\mu^+ K^0$ event is its apparent inconsistency with the absence of clear evidence for such proton decays in the much larger salt-mine detector. But the Mont Blanc detector is at least four times more efficient at seeing $\mu^+ K^0$ than is the IMB water-Cherenkov system. If the Mont Blanc group has seen one $p \rightarrow \mu^+ K^0$ decay in 40 fiducial-ton-years of running, the IMB detector cannot be expected to have seen more than four in the 80 days (700 ton-years) that have been analyzed for this mode; and indeed they do have one ambiguous candidate. “There is not yet any real disagreement between us and IMB,” says Ettore Fiorini (Milan).

Although the branching fraction for proton decay to $\mu^+ K^0$ is predicted in minimal SU(5) to be only a few percent, it becomes far more important in modified versions of SU(5) and in “super-symmetric” grand unified theories. The IMB group has therefore made considerable effort to look for this decay mode, even though the water-Cherenkov detector has a much higher efficiency for seeing $e^+ \pi^0$.

At two conferences in April, the GUTs Workshop in Philadelphia and the APS Spring Meeting in Baltimore, Bruce Cortez and William Foster (both at Michigan) reported on the search for $\mu^+ K^0$ decays in 80 days of running. Having seen one ambiguous event during this period, equally consistent with proton decay or neutrino interaction, the group sets a lower limit of 1.3×10^{31} years on $\tau_{\mu K}$, the partial proton lifetime for this decay mode.

When the K^0 from proton decay to $\mu^+ K^0$ decays to two neutral pions, lots of Cherenkov light would be generated.

But the charged pions from the other decay mode of the short-lived K^0 would produce very little light. The positive pion does, however, frequently decay to μ^+ , which subsequently decays to a positron. Because the muon is relatively long-lived (2 microseconds), the detection of time-delayed Cherenkov showers from the decay positrons of two positive muons turns out to be a good signal for the $\mu^+ K^0$ mode. These delayed muon decay signals also help to distinguish neutrino collisions producing positive pions from p decay to $e^+ \pi^0$.

The Kolar gold-mine detector has now been running for almost three years, corresponding to an exposure of 114 ton-years. Although its design and size are similar to those of the Mont Blanc detector, its iron and tracking layers are significantly thicker, with correspondingly poorer spatial resolution. A year ago the Kolar group—a Tata Institute, Osaka, Tokyo collaboration—reported³ having seen three proton-decay candidates with all tracks fully contained in the detector. The tentative decay modes assigned to these events were $p \rightarrow e^+ \pi^0$, $p \rightarrow \nu(\pi^+ \text{ or } K^+)$ and $n \rightarrow e^+ \pi^-$ (or $p \rightarrow \mu^+ K^0$). At this year's GUTs Workshop, B. V. Sreekantan (Tata Institute) reported that in the last year the group had seen no additional candidate events. If the Kolar group saw one $e^+ \pi^0$ event in 114 ton-years, the IMB should by now have seen about ten in its tenfold greater exposure.

Background. These underground proton-decay detectors need to be concerned primarily about two sources of spurious background signals—neutrinos and muons. Because neutrinos interact so weakly, the flux of cosmic-ray neutrinos is essentially undiminished by burying the detectors deep underground. In fact, neutrinos enter the detectors almost isotropically; they pass through the Earth with equal ease in all directions.

With a mass as large as the IMB water-Cherenkov detector, one expects about one neutrino interaction per day in the fiducial volume. That is in fact the rate at which the IMB group sees neutrino collisions in the water. All but three of these background collisions thus far have produced only single light-generating tracks, or several tracks so close together that they gave the appearance of a single track. Thus they are easily distinguished from the $e^+ \pi^0$ proton decay mode, where one expects to see two tracks going roughly in opposite directions, each with about half the energy of the proton mass. Energy is measured by the number of photoelectrons generated in the photomultipliers; track direction and vertex position can be determined by the spatial and temporal distribution of photomultiplier hits

generated by the cones of Cherenkov light. (The two photons into which the π^0 decays generate two separate Cherenkov cones; but they cannot usually be resolved).

All three two-track events seen thus far in the IMB detector were rejected as $e^+ \pi^0$ proton decays because their directions and energies were inappropriate, and (in two cases) because they also exhibited the time-delayed signal characteristic of the decay sequence $\pi^+ \rightarrow \mu^+ \rightarrow e^+$. About once every five years, however, one expects a neutrino interaction whose products mimic an $e^+ \pi^0$ proton decay so well that they cannot be distinguished in a detector of IMB's size and design. This effectively limits the sensitivity of the IMB detector to a proton lifetime of less than about 10^{33} years.

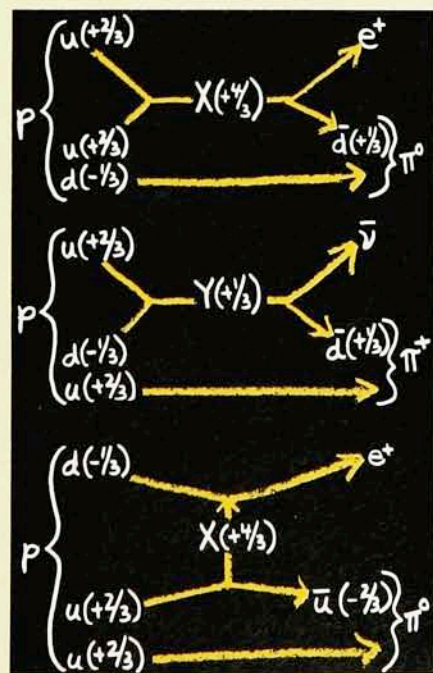
In contrast to the neutrino flux, cosmic-ray muons are strongly attenuated by burying the detectors in the Earth. The Kolar and Mont Blanc detectors are more than three times as deep as the salt-mine detector; thus their muon fluxes are negligible. There had been some concern that the IMB detector was not deep enough to escape a troublesome muon penetration rate. About ten thousand muons do in fact enter the detector every hour. "But we've learned from experience that the muons are no problem," says

Larry Sulak (Michigan). "They turn out, in fact, to be a superb calibration tool." The sensitive water region surrounding the fiducial volume serves as an effective veto region to cull muons entering the detector. One of the advantages of the water-Cherenkov detector is that the Cherenkov cone permits one to distinguish easily between incoming and outgoing tracks. The proportional track chambers of the Kolar and Mont Blanc detectors have more difficulty in determining track direction. The isotropic and homogeneous distribution of the supposed neutrino interactions seen in the IMB detector is strong evidence that few if any of these hundred or so events are muon-induced events for which one failed to see the incoming track.

Theory. One is loath to give up on minimal SU(5) primarily because this theory, in contrast to its active competitors, makes rather definite predictions for proton decay. Minimal SU(5) assumes "the great desert hypothesis." It posits that there is no new physics between the mass scale of electroweak symmetry breaking (about 100 GeV, the masses of the $W^\pm$ and Z gauge (intermediate-vector) bosons that mediate the weak interactions) and the grand-unification symmetry-breaking mass scale (about 10^{14-15} GeV, the masses of the X and Y gauge bosons that are presumed to mediate proton decay). Though the desert hypothesis may seem presumptuous, it has the virtue of limiting the number of unknown parameters in the theory to a degree that definite predictions are possible.

The outstanding predictive success of minimal SU(5) thus far has been its astonishingly accurate prediction of the electroweak mixing angle, θ_w . In the Glashow-Salam-Weinberg electroweak theory, this "Weinberg angle" remains a free parameter. It becomes fixed when one subsumes the electroweak theory in a minimal SU(5) grand unification with the quantum chromodynamic theory of the strong interactions. If one doctors minimal SU(5) to bring it into line with the longer proton lifetime suggested by the IMB results, one loses the clean prediction of the Weinberg angle.

The trouble is that it's too easy to fix up SU(5) to agree with almost any proton lifetime one likes, simply by populating the desert. Spontaneous symmetry breaking in a unified gauge theory requires the existence of spin-zero "Higgs" bosons. Minimal SU(5) assumes the minimum number of such Higgs scalars, with masses not far below those of the spin-one X and Y gauge bosons. But one can easily suppose the existence of lower-mass Higgs scalars that increase the proton lifetime either by pushing the gauge bo-



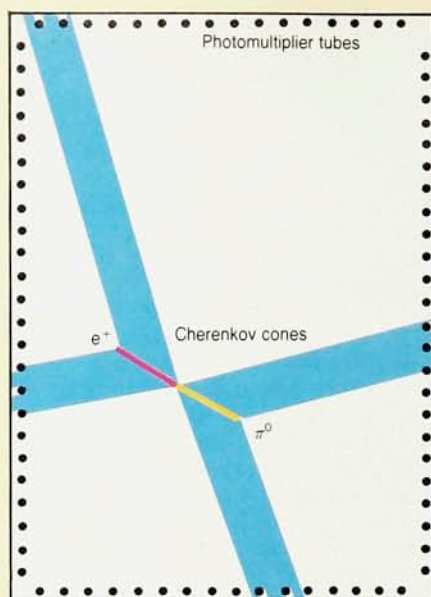
Proton decay in minimal SU(5) is mediated by the virtual formation or exchange of the ultra-heavy, fractionally charged gauge bosons X and Y. The proton consists of two up quarks, u, and one down quark, d. Charges are given in parentheses; antiparticles are indicated by bars. These Feynman diagrams illustrate mechanisms for the decay modes $p \rightarrow e^+ \pi^0$ and $p \rightarrow \bar{\nu} \pi^+$, which are thought to account for about 40% and 16% of proton decays.

sons to higher masses or by themselves replacing the gauge bosons as the dominant mediators of proton decay. In this latter "Higgs dominated" scenario, the proton would decay preferentially to $\mu^+ K^0$ and $K^+ \nu$ rather than $e^+ \pi^0$.

At present we know of three generations of quarks and leptons. One can also complicate SU(5) by positing additional generations or by enlarging the group structure of the theory beyond SU(5) to accommodate additional gauge bosons in the desert. Aside from its apparent underestimation of the proton lifetime, there is additional evidence that something is amiss with minimal SU(5). It predicts correctly the mass ratio of the bottom quark to the tau lepton in the third generation, but the corresponding first- and second-generation mass-ratio predictions are way off.

Some theorists are dissatisfied that SU(5) (minimal or otherwise) offers no natural explanation of why the electroweak and grand-unification mass scales are so wildly different; they are separated by about thirteen orders of magnitude. This problem is addressed by the so-called supersymmetric grand unified theories, which propose the existence of symmetry transformations between bosons and fermions. Every lepton and quark is supposed to have a boson partner—with names such as selectrons and squarks. Similarly, the fundamental bosons would have fermion partners—photinos, gluinos, winos, zenos and the like. Minimal versions of such theories predict a proton lifetime of about 10^{35} years—well beyond the sensitivity of present-day detectors. But this prediction is very sensitive to the configuration of Higgs scalars. The lifetime could be as low as 10^{30} years. The dominant proton decay modes would presumably be $\mu^+ K^0$ and νK^+ , as in the case of Higgs-dominated SU(5).

Georgi describes himself as belonging to the minority of theorists clinging to the belief that minimal SU(5) is not yet beyond hope. He points to the very large uncertainties involved in calculating the proton lifetime from the theory. The predicted lifetime varies as Λ^4 . In the past four years new data on the charmonium and upson spectra and more refined calculations have reduced the best estimate of this QCD scale factor by a factor of three, bringing the lifetime estimate down by two orders of magnitude. When the IMB experiment was first proposed, τ was predicted to be a few times 10^{31} years, in much better agreement with the present experimental limit. Furthermore, the SU(5) calculation of τ depends crucially on the overlap of the wavefunctions one assumes for the quarks confined in the proton. "We



Computer simulation of a proton decay to $e^+ \pi^0$ in the 8-kiloton water Cherenkov detector in a salt mine near Cleveland. The positron (red) and neutral pion (yellow) emerge nearly back-to-back, each with about half the energy of the proton mass. Each track is about two meters long, generating a 42° cone of Cherenkov light detected by the 2048 phototubes arrayed one meter apart near the detector's surface. The detector, built 2000 feet underground by an Irvine-Michigan-Brookhaven collaboration, contains an $18 \times 19 \times 23$ meter volume of highly purified water.

really don't know how to calculate these at all," Georgi argues. He points out that the very light QCD quarks involved in the Feynman diagrams for the basic photon decay interaction (involving exchange of the gauge bosons X and Y) are very different beasts from the "constituent" quarks in the proton, whose effective masses are orders of magnitude greater. There is at present a major effort underway to resolve these calculational difficulties by numerical methods using lattice gauge dynamics. We may well find, Georgi suggests, that such techniques will eventually show the minimal SU(5) proton lifetime to be several orders of magnitude longer than we now believe.

Monopole catalysis. V. A. Rubakov (Institute for Nuclear Research, Moscow) and Curtis Callan (Princeton) have suggested that the superheavy magnetic monopoles predicted by the grand unified theories ought to serve as catalysts for proton decay with an effective cross section on the order of tens of millibarns—a typical hadronic cross section. Therefore, if such a monopole were to pass through a proton-decay detector, it should signal its presence by generating several proton decays in rapid succession.

The IMB group has looked for such nearly coincident proton decays and found none. "A pair of proton decays in

quick succession would be much easier to see than a single decay," Sulak assured us. Assuming that the catalysis cross section is indeed on the order of 10^{-26} cm, the IMB group sets an upper limit of 7×10^{-15} cm $^{-2}$ sr $^{-1}$ sec $^{-1}$ on the monopole flux through their detector. This limit is four orders of magnitude below the (updated) flux suggested by Blas Cabrera's celebrated monopole candidate (see PHYSICS TODAY, June 1982, page 17). The IMB flux limit, however, is highly model-dependent, while Cabrera's experiment makes no assumptions about the hadronic interactions of the monopole.

Other detectors. The 800-ton water-Cherenkov proton-decay detector built by the Harvard-Purdue-Wisconsin collaboration in a Utah silver mine began taking data in January. Unlike the surface array of the IMB system, the phototubes of the HPW detector are arrayed throughout the water volume. This arrangement facilitates the identification of decay modes producing relatively little Cherenkov light. The group plans to report its first $\mu^+ K^0$ results at the end of the summer.

A Japanese group is about to begin operation of a large water-Cherenkov detector in the Kamioka heavy-metal mine near Tokyo. This detector is only $\frac{1}{3}$ the size of the IMB system, but it will be deeper underground, and its photomultiplier tubes will be larger—capturing fifteen times more Cherenkov light than the salt-mine detector, with consequently better particle recognition. A Minnesota-Argonne group has for more than a year been operating a small prototype tracking calorimeter in the Soudan iron mine in Minnesota. With Tufts, Oxford and the Rutherford Lab joining the collaboration, excavation is about to begin for the Soudan-2 detector, a 1000-ton modular array of steel and drift chambers. The plan is ultimately to expand this detector to 5 kilotons. —BMS

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