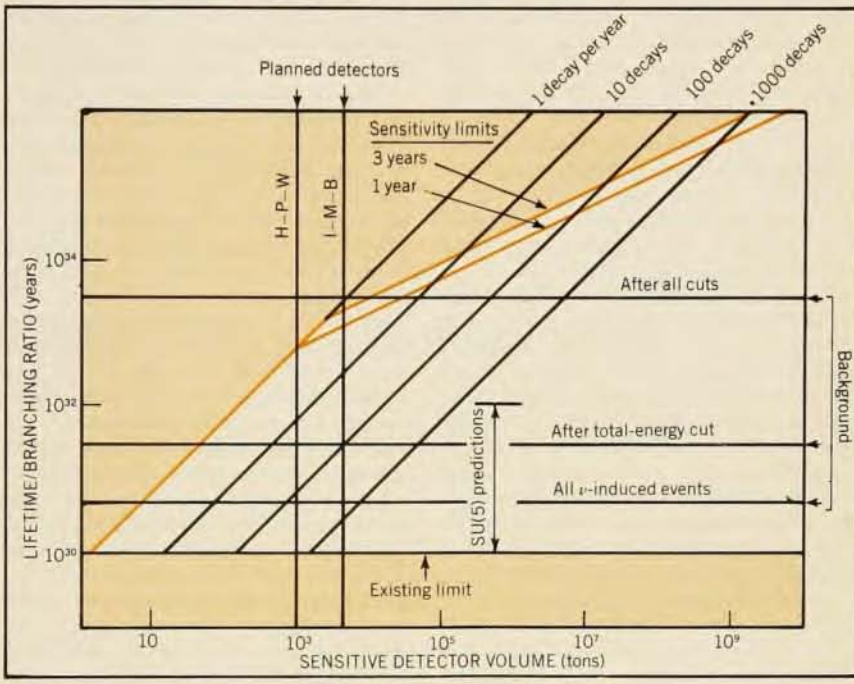
search & discovery

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 approved by DOE.



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.

The grand unification theories put forward in 1974 by Howard Georgi and Sheldon Glashow at Harvard, and by Jogesh Pati (University of Maryland) and Abdus Salam (International Centre for Theoretical Physics, Trieste, and Imperial College, London) both imply that the proton has a finite lifetime. These grand unification schemes attempt to cover the strong, electromagnetic and weak interactions in a single theoretical framework. (Gravitation remains the odd man out.) An exotic consequence of these unification schemes is that hadrons can couple (very weakly) to leptons, without regard for baryon conservation.

The Georgi–Glashow theory uses the unitary group SU(5) to incorporate quarks, leptons, gluons, weak bosons and the photon into a structure that subsumes quantum chromodynamics and the Weinberg–Salam theory of electro-weak interactions. Recent successes of these two gauge theories have focused attention on the Georgi–Glashow theory that unites them.

Enthusiasm for the SU(5) unification scheme has grown in the past few years as the experimental and theoretical estimates of the "Weinberg angle," θ, have converged toward one another. The Weinberg angle is a free parameter in the Weinberg–Salam theory, but it is fixed by the SU(5) unification with the quantum-chromodynamics gauge theory of the strong interaction. The first naive calculations gave $\sin^2\theta = 3/8$. But later in 1974 Georgi, Helen Quinn and Steven Weinberg (all then at Harvard) showed that taking account of renormalization effects brings the prediction down closer to $\sin^2\theta \approx 0.2$. At the time this seemed like a step in the wrong direction, the data being closer to $3/8$. But since that point in time the best experimental value for $\sin^2\theta$ has come down to $0.23 \pm .02$.

Such successes, together with the calculations that appear to put the proton lifetime within reach of experiment, have given great impetus to the search for proton decay. The theory has other enormously attractive features: It offers explanations for two of the great mysteries of nature: the equality of the magnitudes of the electric charges of the proton and the electron, and the apparent predominance of matter over antimatter in the cosmos.

But the experimental search for proton decay antedates these theoretical developments by more than two decades. As Fred Reines (University of California, Irvine), a pioneer of such searches since 1954, puts it, "If there seems to be a conservation law, one ought to check it." Reines and John Vander Velde of the University of Michigan are the two

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spokesmen of the I–M–B collaboration, whose 10-kiloton, $2-million, water-Cerenkov detector will take about a year and a half to complete. A 1974 proposal by Reines and William Kropp of Irvine for a 200-ton detector with a sensitivity of about 10^{31} years had been turned down by the AEC for lack of theoretical motivation, despite the urging of Abdus Salam.

The baryon-nonconserving interactions predicted by the unified theories are very weak indeed. With a predicted proton lifetime of 10^{31} years, a man would have to live several hundred years before he could reasonably expect that a single proton in his body had disintegrated. The long lifetime reflects the enormous mass of the "lepto-quark" that is supposed to mediate this interaction. By extrapolating the hadronic coupling strength of quantum chromodynamics to the ultra-high energy region where it becomes equal to the electro-weak coupling, one arrives at a mass of about 10^{15} GeV (10^{-9} grams, heavier than a bacterium!) for this gargantuan gauge boson.

Because the energy at which the three classes of interactions are expected to become comparable is so very high (10^{15} GeV), the search for the elusive proton decay may be the only way to test the proposed unification theories in the near future. The Pati–Salam and Georgi–Glashow theories predict different decay modes, but they are in rough agreement on the proton lifetime. The calculation of the lifetime is not straightforward in the SU(5) theory. It goes as the fourth power of the mass of the mediating boson, which in turn is estimated by extrapolating coupling strengths over fourteen orders of magnitude in energy. Furthermore the calculation involves the overlap of the quark wave functions inside the proton, something that is not very well known. In the SU(5) theory, two of the three quarks in the proton come together to form a lepto-quark (once every 10^{31} years or so), which then decays into an antiquark and a lepton (usually a positron). The antiquark then teams up with the third quark, emerging as one or more mesons.

If the lifetime of the proton were a mere 10^{16} years, Reines points out, a Geiger counter would suffice to detect its decay. In 1954 Reines, Clyde Cowan and Maurice Goldhaber established the first serious lower limit on the proton lifetime. Using a part of the detector at Los Alamos with which Reines and Cowan eventually verified the existence of the neutrino (1956), they were able to set the lifetime limit at 10^{22} years by looking for ionizing decay fragments in a liquid-scintillator detector 30 meters under ground. Goldhaber is Brookhaven's representative in the present I–M–B collaboration.

One needs to go underground to look for proton decays because cosmic-ray muons can induce interactions that mimic the residues and decay signals left by proton decay. The present lower lifetime limit of about 10^{30} years was determined between 1974 and 1977 with a liquid-scintillation detector 3200 meters under ground in a South-African gold mine. At that depth the cosmic-ray muon flux is negligible, and one need only be concerned about cosmic-ray neutrinos. In fact the detector was originally built by Reines and his collaborators from Case–Western Reserve and the University of Witwatersand (Johannesburg) for the study of cosmic-ray neutrinos.

This experiment searched for nucleon decays simply by looking for the characteristic delayed-coincidence signal resulting from the stopping and subsequent decay of a muon, produced either directly in a nucleon decay or (more likely in the SU(5) theory) as a secondary product from the decay of a pion produced in the nucleon decay. (In all of these experiments one is looking for baryon-nonconserving neutron decays, for example $n \to e^+ \pi^-$, as well as proton decay.) Reines told us that searches at this level of sophistication cannot exceed a sensitivity of about 10^{30} years, irrespective of detector size, because the irreducible neutrino background will generate about one stopping muon per year per 10^{31} nucleons by interactions in the detector. The gold-mine experiment saw six stopping muons in the course of several years of running, a number consistent with the expected neutrino-induced background.

To improve on the present limit one must build detectors that can look at the nucleon decay in more detail, to distinguish it as far as possible from background mimicry. Both the I–M–B and H–P–W collaborations have decided on large-volume water-Cerenkov detectors, about 600 meters under ground. The Cerenkov radiation from the nucleon decay products is to be monitored by an extensive array of photomultiplier tubes. It is expected that position, pulse-height and timing information from the photomultipliers will make possible the reconstruction of decay events in sufficient detail to separate them from the great majority of background signals induced by cosmic-ray muons and neutrinos.

Excavation has already begun (see cover of this issue of PHYSICS TODAY) on the roughly cubical chamber that will hold 10 kilotons of highly purified water for the I–M–B detector in a Morton's salt mine at Fairport Harbor, Ohio. The salt walls, about 20 meters on a side, will be covered with a plastic liner to prevent salt and other contaminants from degrading the optical clarity of the water. Because the I–M–B group has chosen to array its 2400 photomultipliers on the surfaces of the detector rather than dispersing them throughout the volume, it is essential that the attenuation length for Cerenkov photons in the water be better than 30 meters. To this end the water will be continually recirculated through deionizers and reverse-osmosis filters. Scale-model studies at Michigan convince the experimenters that they can maintain the attenuation length at better than 40 meters. Ordinary tap water, for comparison, has a light attenuation length of about 10 to 20 meters. Water clarity is a less crucial concern for the H–P–W collaboration, which plans to distribute its photomultipliers throughout the detector volume.

The Georgi–Glashow model predicts that the most common proton decay mode will be $p \to e^+ \pi^0$. This two-body mode would produce back-to-back, roughly conical showers of Cerenkov light, of approximately equal intensity. (The π^0 decays almost immediately into two photons, but the angle between the two resulting showers is barely resolvable.) The primary properties, then, that distinguish this mode from background are the collinearity of the back-to-back showers, their roughly equal sharing of energy liberated in the proton decay, and the total energy characteristic of the decay.

Energy is measured by the number of photoelectrons generated in the photomultipliers. The direction of each shower can be determined by the difference in arrival time (up to 40 nanoseconds) of different parts of the Cerenkov cone at the photomultiplier array, and by the spatial pattern of photomultiplier hits.

The neatness of the energy and angular criteria that are intended to distinguish the two-body decay modes from background is disturbed by the fact that, except in hydrogen, the decaying nucleon is not initially at rest. The Fermi motion of the more abundant nucleons in oxygen disperses the decay distributions somewhat in angle and energy, permitting that much more background to masquerade as nucleon decay. The oxygen nucleus further degrades the decay signal by capturing a significant fraction of the hadrons produced in the decay before they can get out.

Cosmic-ray background. At the 600-meter depths at which both of the new detectors are to be situated, the cosmic-ray muon flux is still almost one per minute per square meter. High-energy muons that travel a significant distance in the detector are no great problem, because they radiate much more Cerenkov light than would the shorter-range nucleon decay products. More serious is the entry into the detector of neutral hadrons created in nearby material by muon interactions. When these neutral hadrons subsequently interact in the water they may not give themselves away by producing a high-energy charged particle.

The H–P–W group intends to reduce this background by means of an "active shield" around its detector, a thousand-ton concrete vessel that contains the water and is covered by proportional wire detectors. The I–M–B collaboration calculates that it can reduce this background sufficiently with its surface array of photomultipliers, by ignoring events whose vertices lie in the outer two meters of water. This leaves them with a fiducial volume of about 5 kilotons of water. Information about vertex location comes from the size of the cone of Cerenkov light, which spreads as the light travels toward the detectors, and from the arrival time of the light.

Both groups have calculated that they can keep the unresolvable muon-induced background below 0.1 events per year. Their Monte-Carlo simulations further show that the ultimately irreducible background in detectors of this kind comes from the rare—but nonetheless unavoidable—interaction of cosmic-ray neutrinos with nucleons in the detector.

A random nucleon anywhere on or in the Earth interacts with a neutrino about once every 10^{31} years. And so it is with the water in the detectors. Most of the time the products of these weak interactions come out in configurations that are easily distinguished from nucleon decay. But Monte-Carlo simulations have led both groups to conclude that about one percent of the neutrino interactions that produce a Δ (1236) nucleon resonance end up in a back-to-back lepton-pion configuration that cannot be distinguished from a nucleon decay with the resolution of these detectors.

This then is the irredicible background that sets the practical upper limit on the size and sensitivity of detectors of this kind. For every 3×10^{33} nucleons (5 kilotons) one expects about one indistinguishable background event per year, generated by the ubiquitous flux of cosmic-ray neutrinos. The sensitivity of detectors with much fewer than 3×10^{33} nucleons is size-limited; the sensitivity increases linearly with volume. Above this size, the sensitivity is background limited and hence grows only as the square root of the volume.

On these grounds the I–M–B group has concluded that 5 kilotons is the optimal active-volume size for water-Cerenkov detectors. So that's what they have decided to build. In a detector of this size one would see about 150 decays a year (against a background of one event) if the proton lifetime were 10^{31} years and half of all decays were recognized. For a lifetime greater than 10^{33} years, the signal begins to fade into the background.

The H-W-P group, led by Cline, Carlo Rubbia (Harvard) and James Gaidos (Purdue), is proposing a smaller detector (one kiloton of water plus a kiloton of active shield), in hopes of building their device faster and at half the cost. Their silver-mine site in Utah would require no excavation for the smaller detector, which they believe they could construct in one year.

The group has studied the merits of various photomultiplier deployments by Monte-Carlo simulations. Assuming only a 16-meter attenuation length, they conclude that their photomultipliers should be arrayed throughout the detector volume, about a meter apart. With the tubes thus closer to the decay events, they believe they should be able to analyze in detail decay modes that produce less Cerenkov light than does the $e^+ \pi^0$ mode—for example, $p \to e^+ \rho^0$ or $\mu^+ K^0$. They also propose to line their detectors with mirrors, and to run part of the time with a wavelength-shifting ingredient in the water.

Kenneth Lande and Richard Steinberg of the University of Pennsylvania are also looking for proton decays, with a 200-ton, segmented water-Cerenkov detector a mile under ground in the Homestake gold mine in South Dakota. Their detector, which surrounds Ray Davis's famous solar-neutrino detector (see PHYSICS TODAY, December 1978, page 19), was built to look for neutrino bursts from supernovas as well as proton decays. They have recently received DOE funding to enlarge their detector to 800 tons. With its segmented construction the detector's pattern-recognition capability is limited to stopping muons. But with cells of $2 \times 2 \times 1$ meters, Lande believes they will be able to distinguish decay muons from stopping background muons by the total Cerenkov light generated in a single cell.

In December, Marvin Marshak and his colleagues at the University of Minnesota submitted to the DOE a proposal for a "dense" proton-decay detector, to be placed in a Minnesota iron mine. It would consist of an array of proportional gas tubes, with ironized concrete in the interstices. Its compactness and nonliquid character would facilitate shielding and modular construction. —BMS

References

1. J. Learned, F. Reines, A. Soni, Phys. Rev. Lett. **43**, 907 (1979).
2. See, for example, T. J. Goldman, D. A. Ross, Phys. Lett. **84B**, 208 (1979).

Linear electron–positron collider

When the first beams begin circulating in PEP at the Stanford Linear Accelerator Center in March, both sides of the Atlantic will have storage rings producing electron–positron collisions at center-of-mass energies up to 36 GeV. If the rich history of the previous generation of e^+e^- colliding-beam storage rings is any guide, this new energy regime should provide an abundance of interesting physics. But PEP and its Germany cousin PETRA (at DESY, Hamburg) still fall short of the energy range 90–150 GeV that particularly intrigues particle physicists. The European high-energy community hopes to have a storage ring (LEP) of gargantuan size and price tag, capable of achieving these energies by about 1988.

Because the size and cost of storage-ring e^+e^- colliders grow as the square of the center-of-mass energy, various people have argued in recent years that beyond LEP energies one must go to linear rather than ever-larger circular colliding beams. For the past year a group at SLAC has been studying the feasibility of using the existing SLAC two-mile linear accelerator as part of a first-generation linear collider that could achieve 100 GeV several years before LEP. At last October's meeting of HEPAP (High-Energy-Physics Advisory Panel), Burton Richter of SLAC presented their results and their conceptual design for a one-armed "quasi-linear" collider, which would accelerate both positrons and electrons in the one linac, and then bring them together in a collider ring.

While Richter's group is seeking design and preliminary engineering funds from DOE, a group at Novosibirsk, led by Alexander Skrinsky, is urging upon the Soviet government its conception of a two-armed "true" linear collider that might achieve 300 GeV in e^+e^- collisions.

The quadratic growth of cost and size with energy in storage-ring colliders is a consequence of the synchrotron-radiation losses of the circulating electron (and positron) beams. A linear collider eliminates the offending circular motion by having two linear accelerators fire beams at each other more-or-less head on. In such a configuration the cost should grow only linearly with collision energy, for a given luminosity (event rate per unit scattering cross section). It follows therefore that at some energy there must be a cross-over between the costs of linear and storage-ring colliders. Richter believes that given its cost and the quadratic scaling, LEP will be the last and largest e^+e^- storage ring to see the light of day. For higher energies, he feels, only linear colliders will be economically feasible.

There appears to be another limit to the energy one can achieve with e^+e^- (or e^-e^-) storage-ring colliders. With increasing energy, each charge bunch generates ever stronger magnetic fields, which perturb the colliding charge bunch coming in the opposite direction. The strong fields generate synchrotron radiation and nonradiative perturbations in the oncoming beam, which tend to disperse it in energy and direction. The radiation resulting from the beam–beam deflections, which is negligible in present-day machines, has been given in name "beamstrahlung." Although charge bunches in linear colliders also suffer these beam–beam disturbances, they can tolerate larger perturbations