Is a Diamond Really Forever?

Deep underground experiments to measure the lifetime of the proton could change the face of physics, but funding has been delayed

Will the universe always be here? Because of recent developments in theories of elementary particles, physicists believe there is a good chance that it will not, at least as we know it. In the absence of any evidence to the contrary, physicists have always assumed that neutrons (when bound in nuclei) and protons are stable particles that do not decay. Now, it is predicted, all the protons and neutrons in the universe (and the atoms made from them) will eventually decay into lighter elementary particles—electrons, neutrinos, their antiparticles, and photons. As Harvard University theorist Sheldon Glashow asks, "What could be more exciting than knowing if a diamond is forever?"

An unstable proton would not much affect our everyday world because the decay time is known to be more than 10^{30} years. Nonetheless, the significance of observing the decay of the proton would be considerable and extends from cosmology to elementary particles. For this reason, two experiments have been planned that could detect the decay of particles having such long lives, and considerable preliminary work on preparation of sites and equipment is under way. At present, however, progress is not as rapid as could be hoped because the Department of Energy has been slow in approving funds for the full experiments.

One consequence of proton decay comes from the arcane world of elementary particle theory. Physicists have given a high priority to the construction of a single quantum field theory to explain in one fell swoop, as it were, the four known physical forces: gravity, electromagnetism, the strong nuclear force, and the weak force. At present, there is no quantum theory of gravity, so the emphasis is on building a "grand unified" field theory for the other three forces, which are, in any case, the ones of importance in the world of subnuclear physics (see box).

Apart from their simplicity and elegance, which appeal to all scientists, the grand unified theories can account for facts that are only empirically known. The charge of the electron is quantized and exactly equal in magnitude but opposite in sign to that of the proton, but up to now, no theory has explained why. Moreover, the theories seem to be able to account for the increasingly likely proposition that there is very little antimatter in the universe, a situation not explicable by other models. Although physicists caution that the whole grand unified theory business is still "super speculative," the euphoric statement earlier this year by Leon Lederman, the director of the Fermi National Accelerator Laboratory, that "Now we're beginning to understand how it's all put together," seems to describe aptly the mood of many.

The tie-in between grand unified theories and proton decay comes because it is only when the separate quantum field theories of the electromagnetic and weak force, which have already been unified, and of the strong nuclear force are melded together within the larger structure of a grand unified theory that the mechanism for the decay becomes operative.

For these reasons, some theorists are calling measurement of the lifetime of the proton "one of the most important things physicists can do in the next few years—a crucial experiment for physics." (As was pointed out last year by Richard Slansky of the Los Alamos Scientific Laboratory and Pierre Ramond and Murray Gell-Mann of the California Institute of Technology, however, not all grand unified theories necessarily lead to proton decay.)

With such a strong set of motives for measuring proton lifetime, it is doubly encouraging that, by high energy physics standards, the proposed experiments are quite modest in cost, about $1 million. (The fiscal 1980 high energy physics budget within the Department of Energy is more than $300 million.) Unfortunately, the politics of redistributing already allocated funding is holding up approval of the proposals, which were submitted too late in the budget-making process to be included in the original budget. In the meantime, interest in proton decay on the part of European physicists is increasing rapidly, and there is already talk of a race to measure the lifetime of the proton.

The possibility that protons might not live forever is not a new one. E. C. G. Stuckelberg of the University of Geneva 40 years ago and Eugene Wigner of Princeton University 30 years ago conjectured that protons are stable particles. Neutrons in atomic nuclei, unlike free neutrons, do not transform into protons and should therefore also be infinitely long-lived. There is ample empirical evidence that protons are exceptionally stable. If the proton decayed in "only" 10^{16} years, which is a million times the age of the universe, a 70-kilogram human would be the equivalent of a 3 microcurie source of radioactivity, comparable to the activity of compounds in radiotracer experiments.

In the mid-1950's Frederick Reines (now at the University of California at Irvine), the late Clyde Cowan, and Maurice Goldhaber of Brookhaven National Laboratory determined experimentally that protons had a lifetime greater than 10^{22} years. Most recently, John Learned, Reines, and Amarjit Soni of Irvine analyzed data collected over several years from deep underground experiments jointly carried out by collaborating teams from Case Western Reserve University, the University of the Witwatersrand (Johannesburg), and Irvine. They concluded that the limit on the proton lifetime is greater than 10^{30} years.

Whereas these and a few other tests of proton decay were carried out simply because such tests ought to be done in principle, says Reines, the new proposals have a much more specific goal in mind. In 1974, Howard Georgi, Helen Quinn, and Steven Weinberg of Harvard University showed that, in a wide class of grand unified theories, the proton lifetime would automatically be about 10^{32} years. Most recently, Terrence Goldman and Douglas Ross of Caltech, using the leading candidate for a grand unified theory, that developed by Georgi and Glashow 5 years ago, concluded that the proton lives at most 10^{33} years. At last there is a specific lifetime to be looked for. And, as it happens in a coincidence almost too good to be true,

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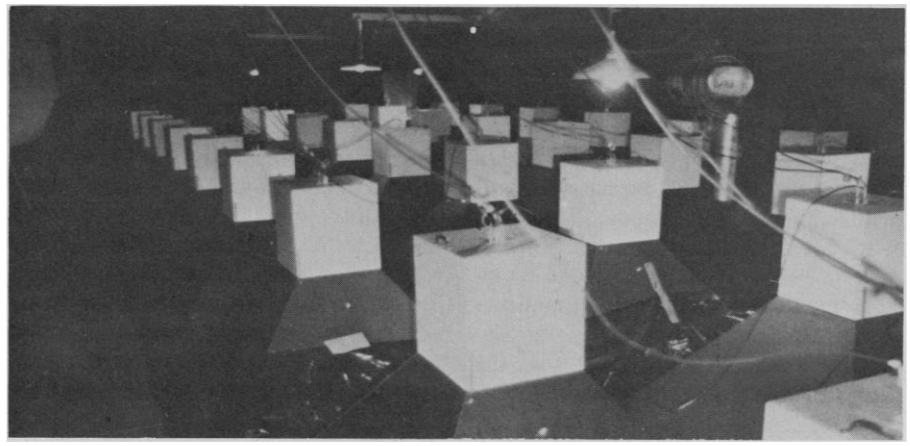
10^{33} years is at the high end of the range of lifetimes that can be detected without building outrageously expensive detectors.

The most straightforward and the least expensive way to search for proton decays is by way of large water detectors. In essence, if a proton lives 10^{33} years, a volume of water containing 10^{33} protons should on the average produce one decay event per year. (A thousand tons of water has about this many protons.) Two groups of researchers—one from Irvine, the University of Michigan, and Brookhaven and the other from Harvard, the University of Minnesota, Purdue University, and the University of Wisconsin—are taking exactly this approach. The first group has proposed a 10,000-ton detector to be placed in a deep underground (600 meters) salt mine in Ohio at a cost of about $1.3 million, and the second has submitted a plan for a smaller detector in a silver mine more than 600 meters below the surface. Because much of the equipment is already on hand and because no digging is required at the site, the amount sought is considerably less, about $300,000.

What is detected is light given off by the rapidly moving decay products of the disintegrated proton or neutron. The light, called Cerenkov radiation, is produced whenever electrically charged particles in a transparent medium travel faster than the speed of light in that medium, which is possible because the speed of light in a liquid or solid is less than that in a vacuum. The possible products of the disintegration are numerous, but calculations by theorists at the European Organization for Nuclear Research (CERN) and Glashow have indicated that about 70 percent of the time the proton decays into a positron (antielectron) and a neutral meson, and about 60 percent of the time the neutron transforms into a positron and a negatively charged meson.

The characteristic signature of the decay of a proton or neutron is therefore a set of two light flashes traceable to the two decay particles. An array of about 1500 photomultiplier tubes can detect the light flashes and determine from them the energy and the direction of motion of the decay products and the location in the water-filled detector of the decay event, says David Cline of Wisconsin. Computer analysis of the pattern of light flashes detected by the array of photomultiplier tubes is needed to distinguish between actual proton or neutron decays and other events that may simulate the decays, that is, the background.

There are two main sources of background. The first, and easiest to deal with, is that due to cosmic rays. These particles arrive at the earth's surface at a rate that would overwhelm the detector. To reduce this flux to a manageable level, experimenters have to go underground. The only particles readily penetrating more than a few meters below the earth's surface are cosmic-ray muons and neutrinos formed when cosmic rays interact with nuclei of the earth's atmosphere. As the depth increases the muon flux is increasingly reduced. It is fruitless to go too deep, however, because the neutrino background, which cannot be diminished in this way, becomes dominant. According to Reines, this critical depth corresponds to being beneath 1500 meters of water. (Since rock is denser than water, the actual depth can be less than 1500 meters.)



The University of Pennsylvania's proton decay experiment.

Even at this depth, there may be something like 10^8 muon-related events per year, and reliance on analysis of the characteristics of the light flashes, such as how many photons they contain, are necessary. In this way, the muon background can be reduced to less than one event per year.

For neutrino-related background events, the problem is more difficult, even though the number of neutrinos interacting with molecules in the water-filled detector is only a few hundred per year. The difficulty is that some neutrino-induced interactions give rise to product particles with properties similar to those emanating from proton or neutron decays. The use of Cerenkov radiation is especially well suited for differentiating this kind of background from true decay events because the light rays travel on the surface of a cone pointing in the particle's direction of motion. This property permits a very complete reconstruction of each event giving rise to a pair of light flashes and hence the ability to determine whether the flashes come from a decay event or a background.

By this means, the limiting neutrino background for a detector of the size under consideration is reduced to one to three events per year, and therefore the upper limit on the measurable proton or neutron lifetime is a shade over 10^{33} years. Building very much larger detectors to increase the sensitivity is not feasible at present, according to Reines, because once the neutrino background limit is reached, sensitivity no longer scales linearly with size. Cline estimates that a lifetime of 10^{34} years might just be measurable with a 100,000-ton detector, but a larger size would be too expensive.

If the lifetime should turn out to be shorter than 10^{33} years, a third American group from the University of Pennsylvania with an experiment already under way may be the first to come up with a measurement. This group has had an experiment running for several months in the Homestake gold mine nearly 1500 meters beneath Lead, South Dakota, according to Kenneth Lande of Pennsylvania. The Homestake gold mine is better known as the site of Raymond Davis's solar neutrino experiment (*Science*, 6 April 1979, p. 42), now in operation for several years.

The Pennsylvania detector is in the form of modules (rather than a single monolithic tank) filled with water and observed by photomultiplier tubes, all of which form a "skin" around Davis's neutrino detector. So far, modules containing a total of 200 tons of water are in routine operation. But the group has just received additional funds to build a larger device of up to 800 tons with more sophisticated electronics and thereby reach a maximum measurable proton lifetime of 3×10^{31} years.

Physicists will be watching the results of these experiments with great interest. But an interested observer might be tempted to ask why the fuss now. For example, the first grand unified theory was published back in 1973, when Abdus

Salam of the International Center for Theoretical Physics in Trieste and Jogesh Pati of the University of Maryland reported their findings. A year later, Georgi and Glashow published their version, which is generally considered a more acceptable model because it incorporates directly the "standard" theories of the weak and strong nuclear forces. Also, in 1974, Georgi, Quinn, and Weinberg showed how, for many grand unified theories, including the Georgi-Glashow model, the requirement that the strengths of all the forces be comparable (see box) could be reconciled with the obvious fact that they are not. As one theorist put it, "They showed the theory makes sense." Gell-Mann said at the time, "There is the smell of a grand new synthesis in the air." Yet it is only in the last year that interest in grand unified theories and proton decay has been so great.

The blossoming of interest comes from two distinctly different regimes of nature: the ultraminiature world of elementary particles and the immensely large scale of astrophysics. One reason for increased confidence in grand unified theories and their predictions is that the quantum field theory of the strong nuclear force and that of the unified electromagnetic-weak (or electroweak) force have been increasingly supported by a great accumulation of experimental data from all the great accelerator centers in the world. And, in the theory of the electroweak force, there is a critical parameter that is not fixed by the theory and whose value is known only by experiment. Grand unified theories, like that of Georgi and Glashow, however, predict a specific value, as calculated by Georgi, Quinn, and Weinberg. In 1974, the experimental and theoretical values were far apart; now they are quite close. The agreement could be a temporary coincidence, but it has been taken as a very encouraging sign.

During the same period, several years of astrophysical observation, according to Gary Steigman of the Bartol Research Foundation at the University of Delaware, have produced no convincing evidence for the existence of large concentrations of antimatter in the universe on distance scales up to clusters of galaxies. Moreover, no one has been able to think up a successful mechanism whereby matter and antimatter could be separated in the early moments of the universe and subsequently maintained on such a large scale. This would cause no problem, except that before the grand unified theories there was no elementary particle model that permitted an excess of matter over antimatter (or vice versa) in the universe.

Built into the grand unified theories is a phenomenon, which has been observed experimentally in studies of K mesons, called CP violation. One consequence of CP violation is that the decay rates of a particle and its antiparticle need not be the same. In the last year, to show how unequal decay rates could lead to an excess of matter over antimatter in our present-day universe, a number of scenarios have been devised combining CP violation and the assumption that the early universe was not in thermal equilibrium. The particles that decay at unequal rates are the particles that mediate the proton decay. In this way, different

What Is Unified in Unified Field Theories

Physicists recognize four basic forces in nature. The electromagnetic force is exceptionally well described by a quantum field theory, quantum electrodynamics. The strong nuclear force, which holds the nucleus together, and the weak force, which is responsible for such phenomena as beta decay of radioactive nuclei and neutrino interactions, are the current foci of intense theoretical and experimental activity. One outcome of this work is a very strong candidate theory to explain the weak and a promising hopeful for the strong nuclear force. But, as separate theories, they leave a number of questions unanswered and are beset with parameters that can only be evaluated by way of experimental data (see accompanying story). Theorists are trying hard to improve the situation by finding a single quantum field theory that underlies all three interactions (and eventually gravity, for which there is now no satisfactory quantum theory)—an achievement that has come to be called a grand unification.*

The placing of electricity and magnetism on an equal footing by the 19th-century Scottish scientist James Clerk Maxwell is usually cited as the prototypical example of unification. Electric and magnetic fields both originate from the existence and motion of electric charge. But there is more to unification than this, because in a fundamental way electric and magnetic fields are not different. A stationary sinusoidal magnetic field, for example, looks like an electromagnetic wave to a moving observer.

Regrettably, no such simple words apply to unification of quantum field theories. An incomplete but essential statement is that at very short distances (or, equivalently, at very high energies, since enormous collision energies are required to force particles close together) there are no apparent differences between the forces. They have the same strengths, for example. A calculation 5 years ago by Howard Georgi, Helen Quinn, and Steven Weinberg of Harvard University indicated that in a wide class of grand unified theories the electromagnetic, strong nuclear, and weak forces are unified in this sense at particle separations of about 10^{-29} centimeter. (A proton is about 10^{-13} centimeter in diameter.) The collision energy needed to achieve such a minute separation is about 10^{15} billion electron volts. The energy is so high because the strong force, which only slowly becomes weaker at high energies, is ordinarily so much greater than those of the other two forces.

Another sense of the meaning of unification comes from consideration of the particles in quantum field theories. Physicists have added to Shakespeare's "All the world's a stage . . . " the phrase "made of fermions and bosons." Fermion and boson are the names of the two most general classes of particles allowed in quantum mechanics. It turns out that the fundamental constituents of matter (quarks, which interact by way of all three forces, and leptons, which do not feel the strong nuclear force) are fermions. In quantum field theories, forces are transmitted by particles of a different type, and these belong to the boson class. The

*Attempts at unified classical (nonquantum) field theories date to 1918 when Hermann Weyl (who was then at the University of Zurich) tried to bring electromagnetism and general relativity (gravity) together in a single geometric formalism. Although Albert Einstein was also devoted to such an enterprise, he was not much concerned with the forces between elementary particles.

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numbers of protons and antiprotons, and thus matter and antimatter, result.

If a positive outcome of the decay experiments should be forthcoming and a proton lifetime in agreement with that predicted by theory found, the implications would be profound. In a talk last year at a seminar on proton stability at the University of Wisconsin, Dimitri Nanopoulos of CERN outlined some of the consequences should the prediction of the Georgi-Glashow model be supported by subsequent verification of the details of the various decay processes and their rates:

- an explanation of why neutrinos have no mass,
- why the electron's charge is quantized,
- why the charges of quarks are either +2/3 or −1/3,
- why quarks and leptons (the class of elementary particles not made of quarks) seem to come in families of four particles consisting of quarks with charges +2/3 and −1/3 and leptons with charges 0 and −1,
- a relation between the masses of some (but not all) of the quarks and leptons, and
- a reason why there may be only six varieties of quarks, that is, three families of particles.

In regard to the last, so far five varieties of quark have been found experimentally, but nobody has had any strong justification for saying how many might be eventually found. Recently, David Schramm of the University of Chicago, Steigman, and their collaborators have collected evidence for the proposition that the abundance of helium-4 in the universe implies a limit on the number of types of neutrinos, namely at most three. In the Georgi-Glashow theory, the number of quark varieties is twice the number of neutrino types.

With so much to gain, it is no surprise that European physicists, who have been successfully challenging American domination of the field by a willingness to spend larger sums of money sooner on big accelerators and detectors, are also interested in getting into the proton decay act. According to Lawrence Sulak, who is a member of the Irvine-Michigan-Brookhaven collaboration, there are at least three European groups thinking hard about the problem. The approach taken by these groups is different from that of the Americans; the Europeans are planning more conventional particle detectors. A French group at the Center for Nuclear Studies at Saclay, for example, wants to use alternating layers of plastic scintillators and marble. A possible site is the Fréjus tunnel, which runs under the Alps, between France and Italy near Turin. Sulak adds that there are also two groups of Japanese scientists working on plans for measuring the proton lifetime, one of which is considering a site under Mt. Fuji.

All in all, there is considerable motivation, both in terms of scientific productivity and of international prestige, to get on with the experiment as soon as possible. Gordon Charlton of the Energy Department is optimistic that both groups will get funded eventually, but, he says, it takes time. Meanwhile, the investigators are chafing at the bit, waiting for the Energy Department to make a decision.—ARTHUR L. ROBINSON

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photon, the quantum of the electromagnetic field, is one such boson. In addition, there are three others that carry the weak force and eight more that transmit the strong nuclear force, for a total of 12 in the most accepted theories.

The properties of the bosons are related to the symmetry of the quantum field equations. The symmetry is of a very abstract kind in a multidimensional, nonphysical coordinate system, but nonetheless it has a strong geometrical character. The tie-in to grand unification is that all the bosons belong to one large family defined by these symmetries. In the leading candidate for a grand unified theory, constructed in 1974 by Georgi and Sheldon Glashow of Harvard, there are 24 bosons. In our everyday, low-energy world, the bosons do not all belong to the same family, and that is why the three forces seem so different.

Symmetry breaking is the name of the mechanism for breaking up one large family of bosons into a number of smaller ones. The most popular kind of symmetry breaking is called spontaneous symmetry breaking and roughly corresponds to the notion that the solutions to the quantum field equations have a lower symmetry than the equations themselves. A pencil standing exactly on end, for example, has an equal probability of falling in any direction (symmetric equation of motion), but it can actually occupy only one of these when it does fall (unsymmetric solution).

Spontaneous symmetry breaking was invoked by Weinberg and by Abdus Salam of Imperial College in London in their work more than a decade ago on the unification of the weak and electromagnetic forces. With the addition of the contributions of several other theorists, the Weinberg-Salam model has become the "standard model" of the "electroweak" interaction and a prototype for what must be incorporated in grand unified theories.†

One of the consequences of spontaneous symmetry breaking is that some of the bosons (all of which, like the photon, initially have no mass) acquire masses. In the standard electroweak theory, the bosons that carry the weak force are thought to be (they have not been observed in any experiment yet) about 80 times as heavy as the proton. The large mass of these particles is what makes the weak force effective only at short distances, which are comparable to size of the nucleus, whereas the electromagnetic force extends over an infinite range.

In the Georgi-Glashow grand unified theory, this scenario is repeated on a larger scale. Spontaneous symmetry breaking gives masses to 12 of the 24 bosons. (The remaining 12 massless bosons are divided into two groups of eight bosons for the strong nuclear force and four bosons for the electroweak force. A second round of symmetry breaking causes the latter to break up into three heavy weak force bosons and the massless photon.) The 12 bosons acquiring a mass in fact become super massive, some 10^{15} times as heavy as the proton, or about 1.5 nanograms. The reason the forces all become equivalent at extremely short distances or high collision energies is that the masses of the bosons become unimportant and the symmetry is restored.

The force transmitted by these superheavy bosons is an all new hyperweak force, a fifth basic interaction in nature. The distinctive feature of the hyperweak force is that it allows quarks to become leptons and vice versa. Since the proton is made up of three quarks, a quark to lepton transformation is the same as the decay of a proton.—A.L.R.

†There has never been a satisfactory quantum field theory of the weak force. It is only when the weak and electromagnetic forces are explained in a unified theory that certain problems of a purely weak force theory are overcome. Glashow, Salam, and Weinberg shared this year's Nobel Prize in Physics for their work on this unified theory.