SCIENCE UNDERGROUND

Remarkable though it may seem, some of our most direct information about processes involving energies far beyond those available at any conceivable particle accelerator and far beyond those ever observed in cosmic rays may come from patiently watching a large quantity of water, located deep underground, for indications of improbable behavior of its constituents. Equally remarkable, our most direct information about the energy-producing processes deep in the cores of stars comes not from telescopes or satellites but from carefully sifting a large volume of cleaning fluid, again located deep underground, for indications of rare interactions with messengers from the sun. In what follows we will explore some of the science behind these statements, learn a bit about how such experiments are carried out, and venture into what the future may hold and how Los Alamos may participate.

The experiments that we will discuss, which can be characterized as searches for exceedingly rare processes, have two features in common: they are carried out deep below the surface of the earth, and they involve a large mass of material capable of undergoing or participating in the rare process in question. The latter feature arises from the desire to increase the probability of observing the process within a reasonable length of time. The underground site is necessary to shield the experiment from secondary cosmic rays. These products of the interactions of primary cosmic rays within our atmosphere would create an overwhelming background of confusing, misleading "noise." Since about 75 percent of the secondary cosmic rays are extremely penetrating muons (resulting from the decays of pions and kaons), effective shielding requires overburdens on the order of a kilometer or so of solid rock (Fig. 1).

What are the goals of the experiments that make worthwhile these journeys into the hazardous depths of mines and tunnels with complex, sensitive equipment? The largest and in many ways the most spectacular experiments—the searches for decay of protons or

the search for rare events

by L. M. Simmons, Jr.

neutrons—are aimed at understanding the basic interactions of nature. The oldest seeks to verify the postulated mechanism of stellar energy production by detecting solar neutrinos—the lone truthful witnesses to the nuclear reactions in our star's core. Smaller experiments investigate double beta decay, the rarest process yet observed in nature, to elucidate properties of the neutrino. Muon "telescopes" will observe the numbers, energies, and directions of cosmic-ray muons to obtain information about the composition and energy spectra of primary cosmic rays. Large neutrino detectors will measure the upward and downward flux of neutrinos through the earth and hence search for neutrino oscillations with the diameter of the earth as a baseline. These detectors can also serve as monitors for signals of rare galactic events, such as the intense burst of neutrinos that is expected to accompany the gravitational collapse of a stellar core.

A site that can accommodate the increasingly sophisticated technology required will encourage the mounting of underground experiments to probe these and other processes in ever greater detail.

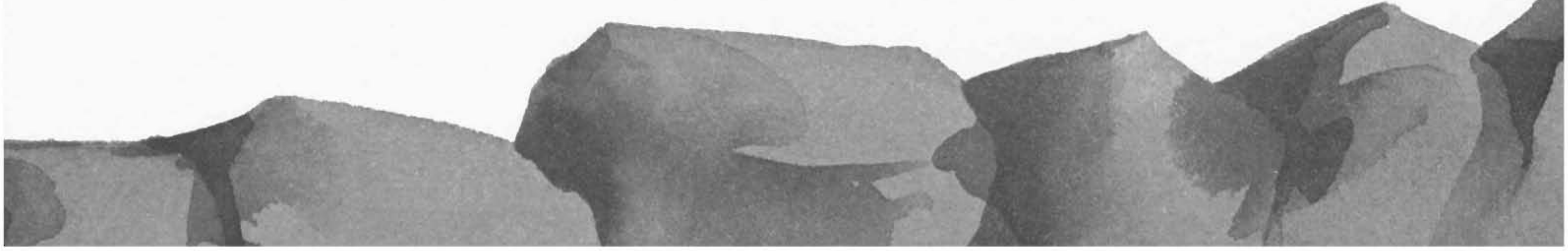
The Search for Nucleon Instability

The universe is thought to be about ten billion (10^{10}) years old, and of this unimaginable span of time, the life of mankind has occupied but a tiny fraction. The lifetime of the universe, while immense on the scale of the lifetime of the human species, which is itself huge on the scale of our own lives, is totally insignificant when compared to the time scale on which matter is known to be stable. It is now certain that protons and (bound) neutrons have lifetimes on the order of 10^{31} years or more. Thus for all practical purposes these particles are totally stable. Why examine the issue any further?

The incentive is one of principle. The mass of a proton or neutron, about 940 MeV/c^2, is considerably greater than that of many other particles: the photon (zero mass), the neutrinos (very small, perhaps zero mass), the electron (0.511 MeV/c^2), the muon (106 MeV/c^2), and the charged and neutral pions (140 MeV/c^2 and 135 MeV/c^2), to name only the most familiar. Therefore, energy conservation alone does not preclude the possibility of nucleon decay. Bearing in mind Murray Gell-Mann's famous dictum that "Everything not compulsory is forbidden," we are obligated to search for nucleon decay unless we know of something that forbids it.

Conservation laws forbidding nucleon decay had been independently postulated by Weyl in 1929, Stueckelberg in 1938, and Wigner in 1949 and 1952. But Lee and Yang argued in 1955 that such laws would imply the existence of a long-range force coupled to a conserved quantum number known as baryon number. (The baryon number of a particle is the sum of the baryon numbers of its quark constituents, $+1/3$ for each quark and $-1/3$ for each antiquark. The proton and the neutron thus have baryon numbers of $+1$.) Lee and Yang's reasoning followed the lines that lead to the derivation of the Coulomb force from the law of conservation of electric charge. However, no such long-range force is observed, or, more accurately, the strength of such a force, if it exists, must be many orders of magnitude weaker than that of the weakest force known, the gravitational force. Thus, although no information was available as to just how unstable nucleons might be, no theoretical argument demanded exact conservation of baryon number.

Los Alamos has the distinction of being the site of the first searches for evidence of nucleon decay. In 1954 F. Reines, C. Cowan, and M. Goldhaber placed a scintillation detector in an underground room at a depth of about 100 feet and set a lower limit on the nucleon lifetime of 10^{22} years. In 1957 Reines, Cowan, and H. Kruse deduced a greater limit of 4×10^{23} years from an improved version of the experiment located at a depth of about 200 feet (in "the icehouse," an area excavated in the north wall of Los Alamos Canyon). Since these early Los Alamos experiments, the limit on the lifetime of the proton has been increased by many orders of magnitude.



Nonconservation of baryon number is also favored as an explanation for a difficulty with the big-bang theory of creation of the universe. The difficulty is that the big bang supposedly created baryons and antibaryons in equal numbers, whereas today we observe a dramatic excess of matter over antimatter (and an equally dramatic excess of photons over matter). In 1967 A. Sakharov pointed out that this asymmetry must be due to the occurrence of processes that do not conserve baryon number; his original argument has since been elaborated in terms of grand unified theories by several authors. The very existence of physicists engaged in searches for nucleon decay is mute testimony to the baryon asymmetry of the universe and, by inference, to the decay of nucleons at some level.

The recent resurgence of interest in the stability of nucleons arises in part from the success of the unified theory of electromagnetic and weak interactions by Glashow, Salam, and Weinberg. This non-Abelian gauge theory, which is consistent with all available data and correctly predicts the existence and strength of the neutral-current weak interaction and the masses of the Z^0 and $W^{\pm}$ gauge bosons, involves essentially only one parameter (apart from the masses of the elementary particles). The measured value of this parameter (the Weinberg angle) is given by $\sin^2\theta_W = 0.22 \pm 0.01$. The success of the electroweak model gave considerable legitimacy to the idea that gauge theories may be the key to unifying all the interactions of nature.

The simplest gauge theory to be applied to unifying the electroweak and strong interactions (minimal SU(5)) gave rise to two exciting predictions. One, that $\sin^2\theta_W = 0.215$, agreed dramatically with experiment, and the other, that the lifetime of the proton against decay into a positron and a neutral pion (the predicted dominant decay mode) lay between 1.6×10^{28} and 6.4×10^{30} years, implied that experiments to detect nucleon decay were technically feasible.

Experimentalists responded with a series of increasingly sensitive experiments to test this prediction of grand unification. What approach is followed in these experiments? Out of the question is the direct production of the gauge bosons assumed to mediate the interactions that lead to nucleon decay. (This was the approach followed recently and successfully to test the electroweak theory.) The grand unified theory based on minimal SU(5) predicts that the masses of these bosons are on the order of 10^{14} GeV/c^2, in contrast to the approximately 10^2 GeV/c^2 masses of the electroweak bosons and many orders of magnitude greater than the masses of particles that can be produced by any existing or conceivable accelerator or by the highest energy cosmic ray. Thus, the only feasible approach is to observe a huge number of nucleons with the hope of catching a few of them in the quantum-mechanically possible but highly unlikely act of decay.

The largest of these experiments (the IMB experiment) is that of a collaboration including the University of California, Irvine, the University of Michigan, and Brookhaven National Laboratory. In this experiment (Fig. 2) an array of 2048 photomultipliers views 7000 tons of water at a depth of 1570 meters of water equivalent (mwe) in the Morton-Thiokol salt mine near Cleveland, Ohio. The water serves as both the source of (possibly) decadent nucleons and as the medium in which the signal of a decay is generated. The energy released by nucleon decay would produce a number of charged particles with so much energy that their speed in the water exceeds that of light in the water (about $0.75c$, where c is the speed of light in vacuum). These particles then emit cones of Cerenkov radiation at directions characteristic of their velocities. The photomultipliers arrayed on the periphery of the water detect this light as it nears the surfaces. From the arrival times of the light pulses and the patterns of their intersections with the planes of the photomultipliers, the directions of the parent charged particles can be inferred. Their energies can be estimated from the amount of light observed, in conjunction with calibration studies based on the vertical passage of muons through the detector. (The impressive sensitivity of such an experiment is well illustrated by the information that the light from a charged particle at a distance of 10 meters in water is less than that on the earth from a photoflash on the moon.)

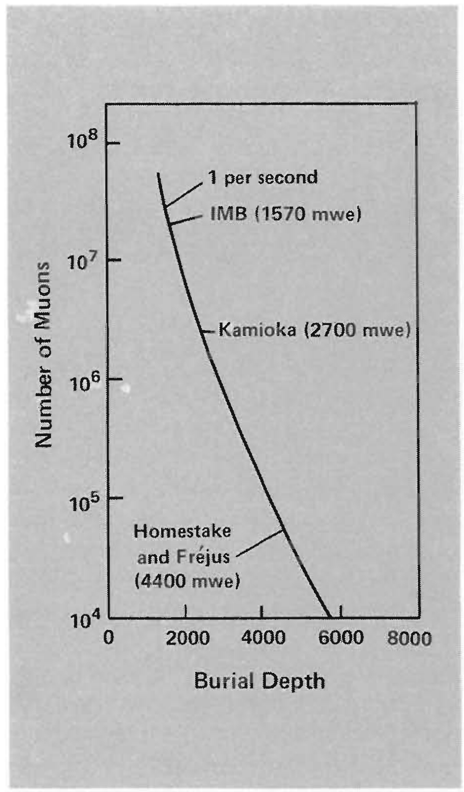


Fig. 1. For some experiments the only practical way to sufficiently reduce the background caused by cosmic-ray muons is to locate the experiments deep underground. Shown above is the number of cosmic-ray muons incident per year upon a cube 10 meters on an edge as a function of depth of burial. By convention depths of burial in rocks of various densities are normalized to meters of water equivalent (mwe). The depths of some of the experiments discussed in the text are indicated.

This "water Cerenkov" detection scheme was chosen in part for its simplicity, in part for its relatively low cost, and in part for its

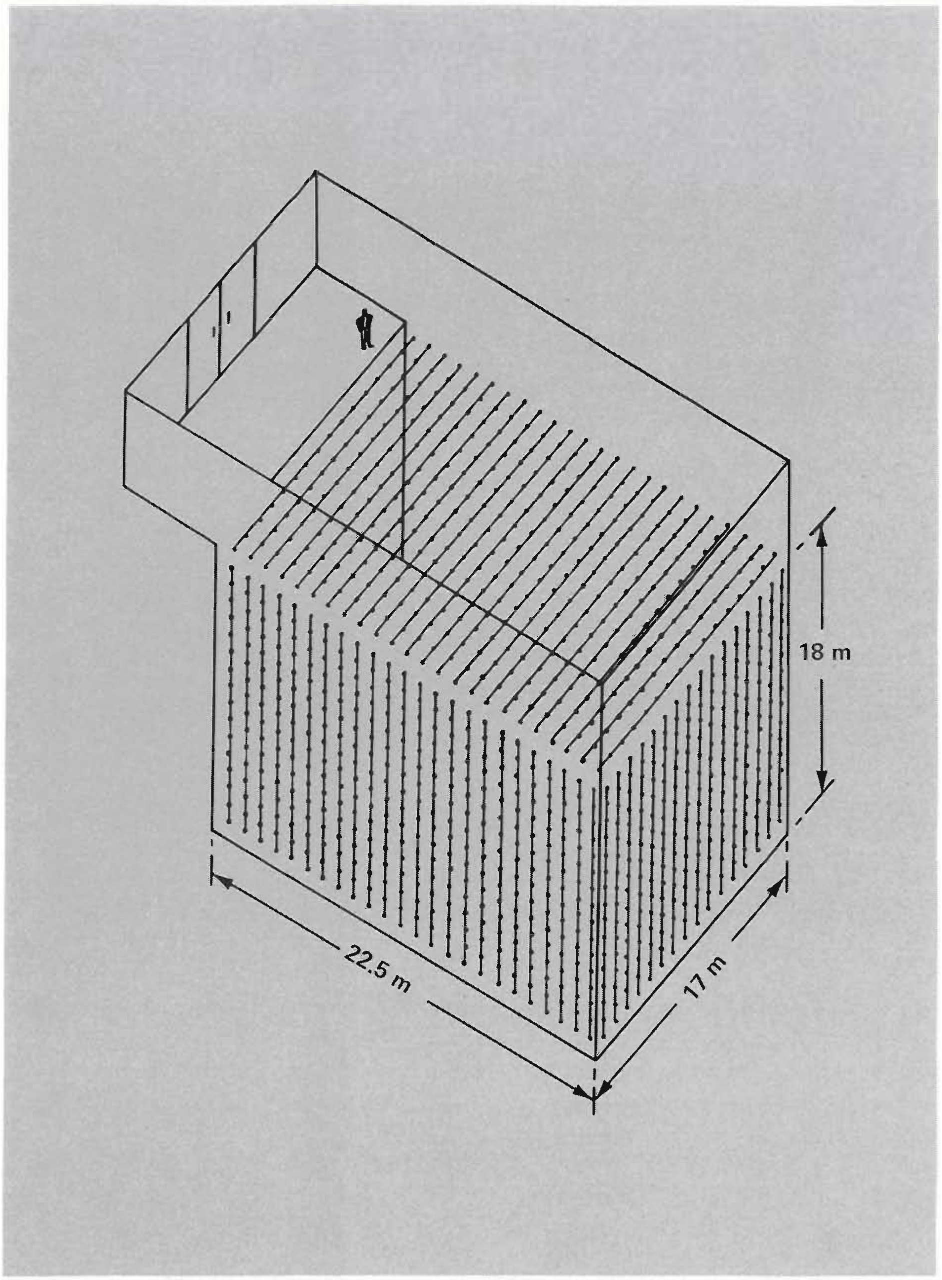


Fig. 2. Schematic view of the IMB nucleon-decay detector. A total of 2048 5-inch photomultipliers are arrayed about the periphery of 7000 tons of water contained within a plastic-lined excavation at a depth of 1570 mwe in a salt mine near Cleveland, Ohio. The photomultipliers monitor the water for pulses of Cerenkov radiation, some of which may signal the decay of a proton or a neutron. (From R. M. Bionta et al., "IMB Detector—The First 30 Days," in **Science Underground (Los Alamos, 1982)** *(American Institute of Physics, New York, 1982)).*

high efficiency at detecting the electrons that are the ultimate result of the $p \rightarrow e^+ + \pi^0$ decay. (The neutral pion immediately decays to two photons, which produce showers of electrons in the water.) Note, however, that although this two-body decay is especially easy to detect because of the back-to-back orientation of the decay products, it must be distinguished, at the relatively shallow depth of the IMB experiment, among a background of about 2×10^5 muon-induced events per day. (The lower limit on the proton lifetime predicted by minimal SU(5) implies a maximum rate for $p \rightarrow e^+\pi^0$ of several events per day.)

Another experiment employing the water Cerenkov detection scheme is being carried out at a depth of 2700 mwe by a collaboration including the University of Tokyo, KEK (National Laboratory for High-Energy Physics), Niigata University, and the University of Tsukuba. The experiment is located under Mt. Ikenayama in the deepest active mine in Japan, the Kamioka lead-zinc mine of the Mitsui Mining and Smelting Co. Although the mass of the water viewed in this experiment (3000 tons) is substantiallly less than that in the IMB experiment, its greater depth of burial results in lower background rates. More important, 1000 20-inch photomultipliers are deployed at Kamioka (Fig. 3), in contrast to the 2048 5-inch photomultipliers at IMB. As a result, a ten times greater fraction of the water surface at Kamioka is covered by photocathode material, and the light-collection efficiency is greater by a factor of about 12. Thus the track detection and identification capabilities of the Kamioka experiment are considerably better.

To date neither the IMB experiment nor the Kamioka experiment has seen any candidate for $p \rightarrow e^+\pi^0$. These negative results yield a proton lifetime greater than 2×10^{32} years for this decay mode, well outside the range predicted by the grand unified theory based on minimal SU(5). Since this theory has a number of other deficiencies (it fails to predict the correct ratio for the masses of the light quarks and predicts a drastically incorrect ratio for the number of baryons and photons produced by the big bang), it is therefore now thought to be the wrong unification model. Other models, at the current stage of their development, have too little predictive power to yield decay rates that can be unambiguously confronted by experiment. The question of nucleon decay is now a purely experimental one, and theory awaits the guidance of present and future experiments.

The cosmic rays that produce the interfering muons also produce copious quantities of neutrinos (from the decays of pions, kaons, and muons). No amount of rock can block these neutrinos, and some of them interact in the water, mimicking the effects of proton decay. Estimates of this background as a function of energy are based on calculations of the flux of cosmic-ray-induced neutrinos from the known flux of primary cosmic rays. Although these calculations enjoy reasonable confidence, no accurate experimental data are available as a check. Full analyses of the neutrino backgrounds in the proton-decay experiments will provide the first such verification. Whether new effects in neutrino astronomy will be discovered from the spectrum of neutrinos incident on the earth remains to be seen. Thus nucleon-decay experiments may open a new field, that of neutrino astronomy.

The water Cerenkov experiments have detected several events that could possibly be interpreted as nucleon decays by modes other than $e^+\pi^0$ (Table 1). It is also possible that these events are induced by neutrinos. Although their configurations are not easily explained on that basis, their total number is consistent with the rate expected from the calculated neutrino flux.

A perusal of Table 1 shows that the IMB and Kamioka experiments yield different lifetime limits and do not see the same number of candidate events for the various decay modes. This is not surprising since the two also differ in aspects other than those already mentioned. The Kamioka experiment can more easily distinguish events with multiple tracks, such as $p \rightarrow \mu^+\eta$, which is immediately followed by decay of the η meson

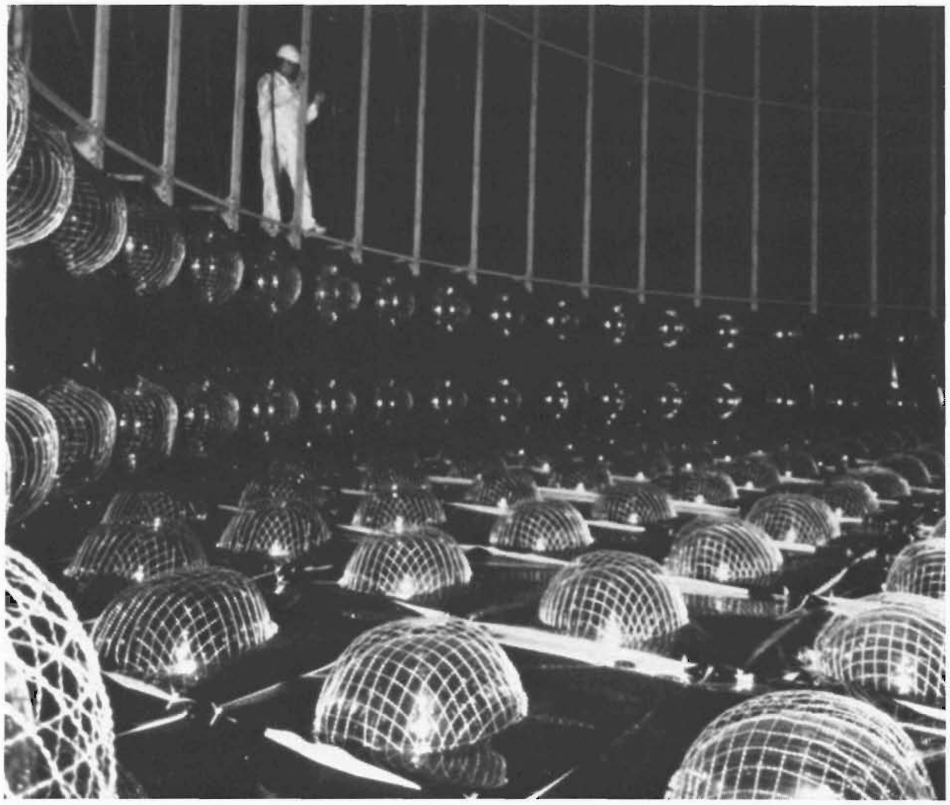


Fig. 3. Photograph of the Kamioka nucleon-decay detector under construction at a depth of 2700 mwe in a lead-zinc mine about 300 kilometers west of Tokyo. Already installed are the bottom layer of photomultipliers and two ranks of photomultipliers on the sides of the cylindrical volume. The wire guards around the photomultipliers protect the workers from occasional implosions. The upper ranks and top layer of photomultipliers were installed from rafts as the water level was increased. The detector contains a total of 1000 20-inch photomultipliers. (Photo courtesy of the Kamioka collaboration.)

Table 1

Some current results of the Kamioka and IMB experiments. Listed for each decay mode are the number of candidate events detected (in brackets) and the deduced lifetime limit.

Decay Mode	Number of Events and Lifetime Limit (years)	
	Kamioka	IMB
$p \rightarrow e^+\pi^0$	[0] 3×10^{31}	[0] 2×10^{32}
$p \rightarrow \mu^+\pi^0$	[0] 2×10^{31}	[0] 1×10^{32}
$p \rightarrow \mu^+K^0$	[1] 1×10^{31}	[1] 6×10^{31}
$p \rightarrow \mu^+\eta$	[1] 8×10^{30}	[0] 9×10^{31}
$p \rightarrow \nu K^+$	[2] 7×10^{30}	[3] 1×10^{31}
$p \rightarrow \nu\pi^+$	[5] 3×10^{30}	---
$n \rightarrow e^+\pi^-$	[0] 1×10^{31}	[4] 2×10^{31}
$n \rightarrow \nu K^0$	[0] 3×10^{30}	[3] 8×10^{30}

Branching ratio	Reaction	Neutrino energy, flux
(99.75%)	$p + p \rightarrow d + e^+ + \nu_e$	0 - 0.42 MeV, $607 \times 10^8/cm^2 \cdot s$
	or	
(0.25%)	$p + p + e^- \rightarrow d + \nu_e$	1.44 MeV, $1.5 \times 10^8/cm^2 \cdot s$
	$d + p \rightarrow {}^3He + \gamma$	
(86%)	${}^3He + {}^3He \rightarrow 2p + {}^4He$	
	or	
(14%)	${}^3He + {}^4He \rightarrow {}^7Be + \gamma$	
(99.89%)	${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	0.86 MeV, $43 \times 10^8/cm^2 \cdot s$
	${}^7Li + p \rightarrow 2{}^4He + \gamma$	
	or	
(0.0.11%)	${}^7Be + p \rightarrow {}^8B + \gamma$	
	${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$	0 - 14.0 MeV, $0.056 \times 10^8/cm^2 \cdot s$
	${}^8Be^* \rightarrow 2{}^4He$	

Fig. 4. The proton-proton chain postulated by the standard solar model as the principal mechanism of energy production in the sun. The net result of this series of nuclear reactions is the conversion of four protons into a helium-4 nucleus, and the energy released is carried off by photons, positrons, and neutrinos. Predicted branching ratios for competing reactions are listed. Some of the reactions in this chain produce neutrinos; these particles, and their energies and predicted fluxes at the earth, are shown in blue.

by a number of modes. On the other hand, the IMB experiment has been in progress for a longer time and is thus more sensitive to decay modes with long lifetimes.

The IMB collaboration has recently installed light-gathering devices around each photomultiplier and will soon double the number of tubes with the goal of increasing the light-collection efficency by a factor of about 6. At Kamioka accurate timing circuits are being installed on each photomultiplier to record the exact times of arrival of the light signals. As a result, more and better data can be expected from both experiments in the coming months.

What else does the future hold? A third water Cerenkov experiment has been set up in the Silver King mine at Park City, Utah, by a collaboration including Harvard University, Purdue University, and the University of Wisconsin. Although the mass of water viewed in this experiment is only about 800 tons, the 704 phototubes are distributed throughout the volume, giving very good light-collection efficiency and special sensitivity to decay modes producing muons. Only preliminary data are available from this experiment.

A European collaboration (including Aachen, Orsay, Ecole Polytechnique, Saclay, and Wuppertal University) is constructing, at a depth of 4400 mwe in a specially excavated room in the Fréjus Tunnel near Modane, France, a 1000-ton detector of a different design. This design will allow location of particle tracks with an accuracy of less than a centimeter. (The corresponding "resolution" of water Cerenkov detectors is about 50 centimeters.) Moreover, the detector will provide data on energy losses along the particle tracks; such data are valuable for particle identification. An American-British collaboration (known as Soudan II and including Argonne National Laboratory, the University of Minnesota, Oxford University, Rutherford-Appleton Laboratory, and Tufts University) has just begun constructing a somewhat similar detector in the Soudan iron mine in northern Minnesota. Since these detectors view relatively small numbers of nucleons (fewer than 6×10^{32}), they can record reasonable event rates only for those decay modes (if any) with lifetimes considerably less than 10^{32} years.

Despite the hopes for these newer experiments, the IMB and Kamioka results to date imply that accurate investigation of most nucleon decay modes demands multikiloton detectors with very fine-grained resolution. Such detectors are not yet on the drawing boards, but many ideas are being discussed and preliminary design work has been begun by several groups in the United States and abroad. These second-generation detectors, which will be very expensive and take years to build, will be sensitive to other rare processes in addition to nucleon decay. It can be argued that experimental devices of this delicacy and complexity cannot realistically be built and operated, as the present generation has been, in the environment of a working mine since support facilities approximating those of a major laboratory will be required.

The Solar Neutrino Mystery

The light from the sun so dominates our existence that all human cultures have marveled at its life-giving powers and have concocted stories explaining its origins. Scientists are no different in this regard. How do we explain the almost certain fact that the sun has been radiating energy at essentially the present rate of about 4×10^{26} joules per second for some 4 to 5 billion years? Given a solar mass of 2×10^{30} kilograms, chemical means are wholly inadequate, by many orders of magnitude, to support this rate of energy production. And the gravitational energy released in contracting the sun to its present radius of about 7×10^5 kilometers could provide but a tiny fraction of the radiated energy. The only adequate source is the conversion of mass to energy by nuclear reactions.

This answer has been known for a generation or two. Through the work of Hans Bethe and others in the 1930s and of many workers since, we have a satisfactory model for solar energy production based on the thermonuclear fusion of hydrogen, the most abundant element in the universe and in most stars. The product of this proton-proton chain (Fig. 4) is helium, but further nuclear reactions yield heavier and heavier elements. Detailed models of these processes are quite successful at explaining the observed abundances of the elements. "Thus it is possible to say [with W. A. Fowler] that you and your neighbor and I, each one of us and all of us, are truly and literally a little bit of stardust."

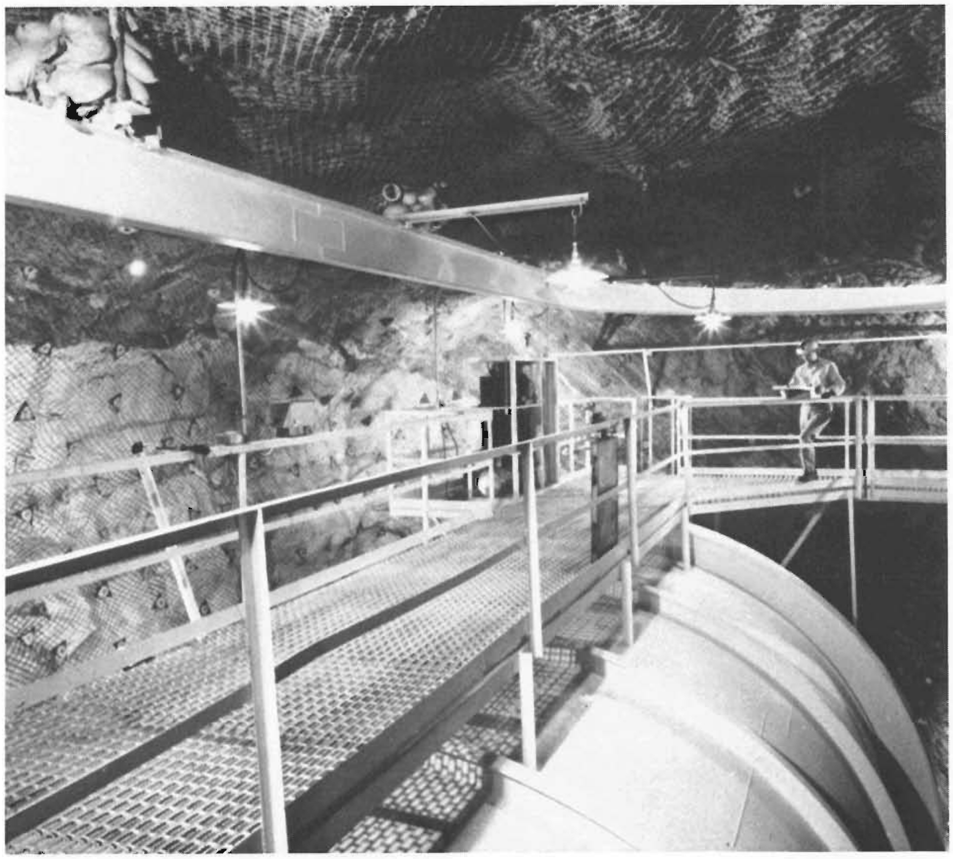


Fig. 5. A view of the solar neutrino experiment located at a depth of 4850 feet in the Homestake gold mine. The steel tank contains 380,000 liters of perchloroethylene, which serves as a source of chlorine atoms that interact with neutrinos from the sun. Nearby is a small laboratory where the argon atoms produced are counted. (Photo courtesy of R. Davis and Brookhaven National Laboratory.)

The successes of the standard solar model may, however, give us misplaced confidence in its reality. It is all very well to study nuclear reactions and energy transport in the laboratory and to construct elaborate computational models that agree with what we observe of the exteriors of stars. But what is the direct evidence in support of our story of what goes on deep within the cores of stars?

The difficulties presented by the demand for direct evidence are formidable, to say the least. Stars other than our sun are hopelessly distant, and even that star, although at least reasonably typical, cannot be said to lie conveniently at hand for the conduct of experiments. Moreover, the sun is optically so thick that photons require on the order of 10 million years to struggle from the deep interior to the surface, and the innumerable interactions they undergo on the way erase any memory of conditions in the solar core. Thus, all conventional astronomical observations of surface emissions provide no direct information about the stellar interior. The situation is not hopeless, however, for several of the nuclear reactions in the proton-proton chain give rise to neutrinos. These particles interact so little with matter that they provide true testimony to conditions in the solar core.

The parameters incorporated in the standard solar model (such as nuclear cross sections, solar mass, radius, and luminosity, and elemental abundances, opacities (from the Los Alamos Astrophysical Opacity Library), and equations of state) are known with such confidence that a calculation of the solar neutrino spectrum is expected to be reasonably accurate. At the moment only one experiment in the world—that of Raymond Davis and his collaborators from Brookhaven National Laboratory—attempts to measure any portion of the solar neutrino flux for comparison with such a calculation. Located at a depth of 4400 mwe in the Homestake gold mine in Lead, South Dakota, this experiment (Fig. 5) detects solar neutrinos by counting the argon atoms from the reaction

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^- ,$$

which is sensitive primarily to neutrinos from the beta decay of boron-8 (see Fig. 4). Since chlorine-37 occurs naturally at an abundance of about 25 percent, any compound containing a relatively large number of chlorine atoms per molecule and satisfying cost and safety criteria can serve as the target. The Davis experiment uses 380,000 liters of perchloroethylene (C_2Cl_4).

You might well ask why this reaction occurs at a detectable rate. All the solar neutrinos incident on the tank of perchloroethylene have made the journey from the solar core to the earth and then through 4850 feet of solid rock with essentially no interactions, and the neutrinos from the boron-8 decay constitute but a small fraction of the total neutrino flux. What is the special feature that makes this experiment possible? Apart from the large number of target chlorine atoms, it is the existence of an excited state in argon-37 that leads to an exceptionally high cross section for capture by chlorine-37 of neutrinos with energies greater than about 6 MeV. Figure 4 shows that the only branch of the proton-proton chain producing neutrinos with such energies is the beta decay of boron-8. The standard solar model predicts a rate for the reac-

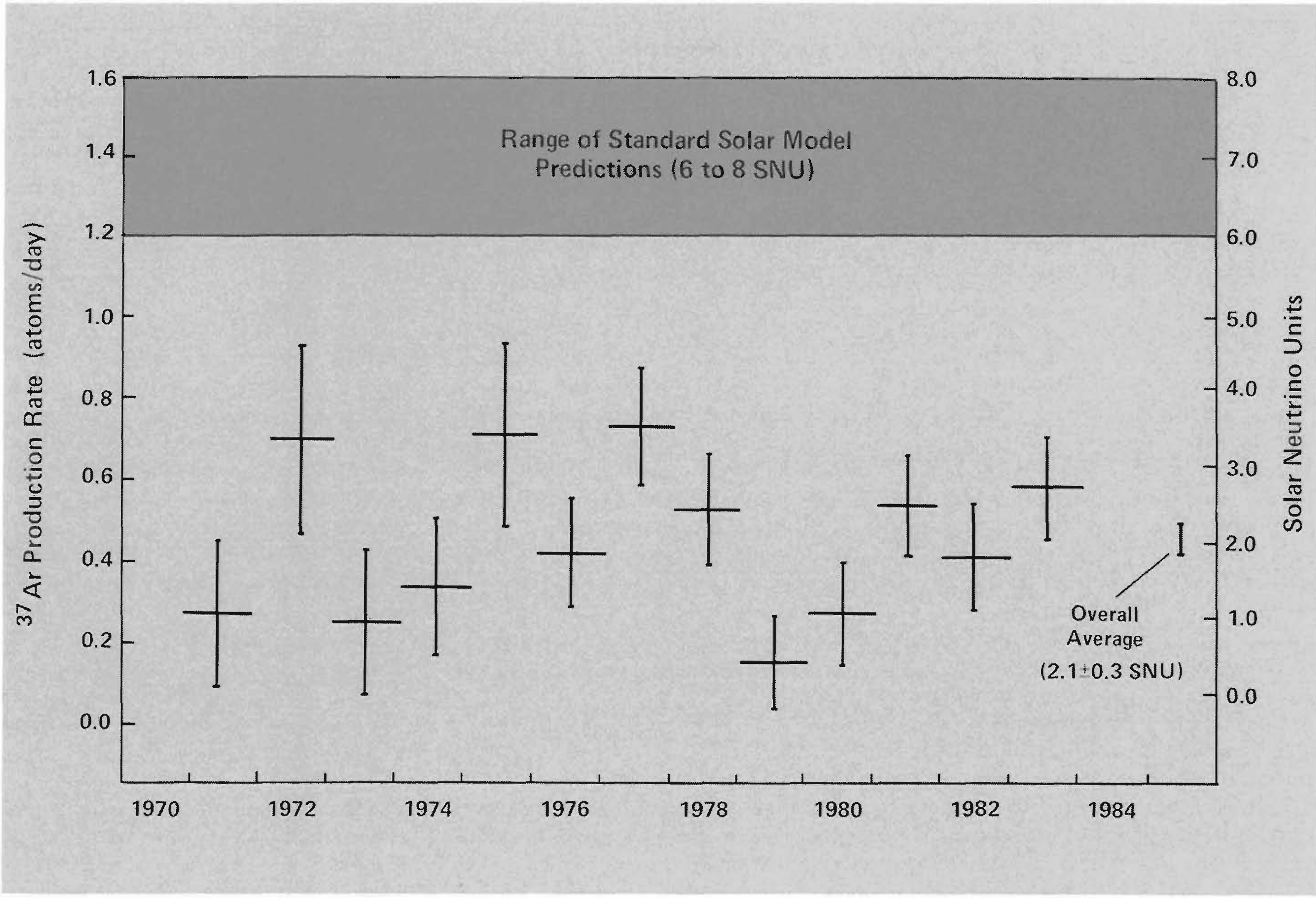


Fig. 6. Experimental results from the Homestake solar neutrino experiment expressed as yearly averages. The discrepancy between the experimental results and the predictions of the standard solar model has not yet been explained. (From R. Davis, Jr., B. T. Cleveland, and J. K. Rowley, "Report on Solar Neutrino Experiments," presented at the Conference on Intersections Between Particle and Nuclear Physics, Steamboat Springs, Colorado, May 1984 and to be published in the conference proceedings by the American Institute of Physics.)

tion of about 7×10^{-36} per target atom per second (7 solar neutrino units, or SNUs), which corresponds in the Davis experiment to an expected argon-37 production rate of about forty atoms per month.

It may seem utterly miraculous that such a small number of argon-37 atoms can be detected in such a large volume of target material, but the technique is simple. About every two months helium is bubbled through the tank to sweep out any argon-37 that has been formed. The resulting sample is purified and concentrated by standard chemical techniques and is monitored for the 35-day decay of argon-37 by electron capture. Great care is taken to distinguish these events by pulse height, rise time, and half-life from various background-induced events. As part of the recovery technique argon-36 and -38 are inserted into the tank in gram quantities or less to monitor the recovery efficiency (about 95 percent). An artificially introduced sample of 500 argon-37 atoms has also been recovered successfully. Indeed, the validity of the technique has been verified by continual scrutiny over more than fifteen years.

The Homestake experiment has provided the scientific world with a long-standing mystery: its results are significantly and consistently lower than the predictions of the standard solar model (Fig. 6). So what's wrong?

The first possibility that immediately suggests itself, that the Davis experiment contains some subtle mistake, cannot be eliminated. But it must be dismissed as unlikely because of the careful controls incorporated in the experiment and because of the years of independent scrutiny that the experiment has survived. The possibility that the parameters employed in the calculation might be in error has been repeatedly examined by careful investigators seeking to explain the mystery (and thereby make reputations for themselves). However, no one has suggested corrections that are large enough to explain the discrepancy.

Another possibility is that the standard solar model is wrong. The reaction that gives rise to boron-8 is inhibited substantially by a Coulomb barrier and is thus extraordinarily sensitive to the calculated temperature at the center of the sun. A tiny change in this temperature or a small deviation from the standard-model value of the solar core composition would be sufficient to change the rate of production of boron-8 and thus the neutrino flux to which the Davis experiment is primarily sensitive. A whole array of "nonstandard" solar models is available that can change the predicted boron-8 neutrino flux, but there is no way to choose among them. They may all be wrong. A more complete investigation of the solar neutrino spectrum will provide the quantitative constraints needed for the standard solar model of the future.

Finally, we mention one other possible solution to the solar neutrino mystery. The results of the Homestake experiment have been interpreted on the basis of our current understanding of neutrinos, which is far from complete. We do not know, for example, whether they are massless or simply very light. If neutrinos have nonzero masses, the electron neutrinos produced in the proton-proton chain may undergo interactions during their journey to the earth that produce a mixture of electron, muon, and tau neutrinos. Such "oscillations," if they occur, could account for the low solar neutrino flux measured by the Homestake experiment, which detects only electron neutrinos.

Neutrino oscillations are being sought enthusiastically because they can provide much-needed information about the masses of these elusive particles. The experiments currently in progress at Los Alamos (see "Experiments To Test Unification Schemes") and elsewhere examine the neutrinos produced by accelerators and nuclear reactors. Solar neutrino experiments, however, satisfy two criteria (long path length and low neutrino energy) for investigating the phenomenon at an unparalleled level of sensitivity.

Future Solar Neutrino Experiments

Obviously, much remains unknown about solar neutrinos. In particular we lack complete information about the flux of neutrinos from other reactions in the proton-proton chain. Los Alamos has now formed a new collaboration and proposes to provide this information. The collaboration includes, in addition to Los Alamos scientists, members of the Homestake team and scientists from Oak Ridge National Laboratory, the Institute for Advanced Study, the University of Tennessee, the University of Chicago, the California Institute of Technology, and Princeton University. The new experiments are based on neutrino capture by gallium-71 and bromine-81.

According to the standard solar model, the preponderance of solar neutrinos arises from the first reaction in the proton-proton chain, the thermonuclear fusion of two protons to form a deuteron. A thorough test of the solar model must include measurement of the neutrino flux from this reaction, the rate of which, although essentially independent of the details of the model (varying by at most a few percent), involves the basic assumption that hydrogen burning is the principal source of solar energy.

The preferred reaction for investigating the initial fusion in the proton-proton chain is

$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^- ,$$

which has a threshold of 233 keV, well below the maximum energy of the *pp* neutrinos. Calculations based on the standard solar model and the relevant nuclear cross sections predict a capture rate of about 110 SNU, of which about two-thirds is due to the *pp* reaction, about one-third to the electron capture reaction of beryllium-7, and a very small fraction to the other neutrino-producing reactions.

Several years ago members of the Homestake team, in collaboration with scientists from abroad, carried out a pilot experiment to assess a technique suggested for a solar neutrino experiment based on this reaction. Germanium-71 was introduced into a solution of over one ton of gallium (as $GaCl_3$) in hydrochloric acid. In such a solution germanium forms the volatile compound $GeCl_4$, which was swept from the tank with a gas purge. By fairly standard chemical techniques, a purified sample of GeH_4 was prepared for monitoring the 11-day decay of germanium-71 by electron capture. The pilot experiment clearly demonstrated the feasibility of the technique.

Why has the full-scale version of this important experiment not been done? The trouble, as usual, is money. The original estimates indicated that achieving an acceptable accuracy in the measured neutrino flux would require about one neutrino capture per day, which corresponded to 45 tons of gallium as a target. Gallium is neither common nor easy to extract, and the cost of 45 tons was about $25,000,000, an amount that proved unavailable. Nor did the suggestion to "borrow" the required amount of gallium succeed (despite the fact that only one gallium atom per day was to be expended), and the collaboration disbanded. (Incidentally, a team of Soviet scientists has obtained 60 tons of gallium and has a pilot experiment well along.)

The chances of mounting a gallium experiment seem brighter today, however, since recent Monte Carlo simulations have shown that an accuracy of 10 percent in the measured neutrino flux is possible from a four-year experiment incorporating improved counting efficiencies and reduced background rates and involving only 30 tons of gallium. Moreover, changes in the price of gallium make it likely that this amount of material might be had for less than $15,000,000. Encouraged by these developments, Los Alamos scientists are joining forces with Davis and other members of the original gallium collaboration to carry out the experiment.

As mentioned above, a gallium experiment detects neutrinos from both proton fusion and beryllium-7 decay. To determine the individual rates of the two reactions requires a separate measurement of the neutrinos from the latter. A reaction that satisfies the criterion of being sensitive primarily to the beryllium-7 neutrinos is

$$\nu_e + {}^{81}\mathrm{Br} \rightarrow {}^{81}\mathrm{Kr} + e^- .$$

Results from this bromine experiment are essential to an unambiguous test of the standard solar model.

The chemical techniques needed in the bromine experiment are substantially identical to those employed in the chlorine-37 experiment, and therefore the feasibility of this aspect of the experiment is assured. However, since krypton-81 has a half-life of 200,000 years, counting a small number of atoms by radioactive decay techniques is out of the question. Fortunately, another tech-

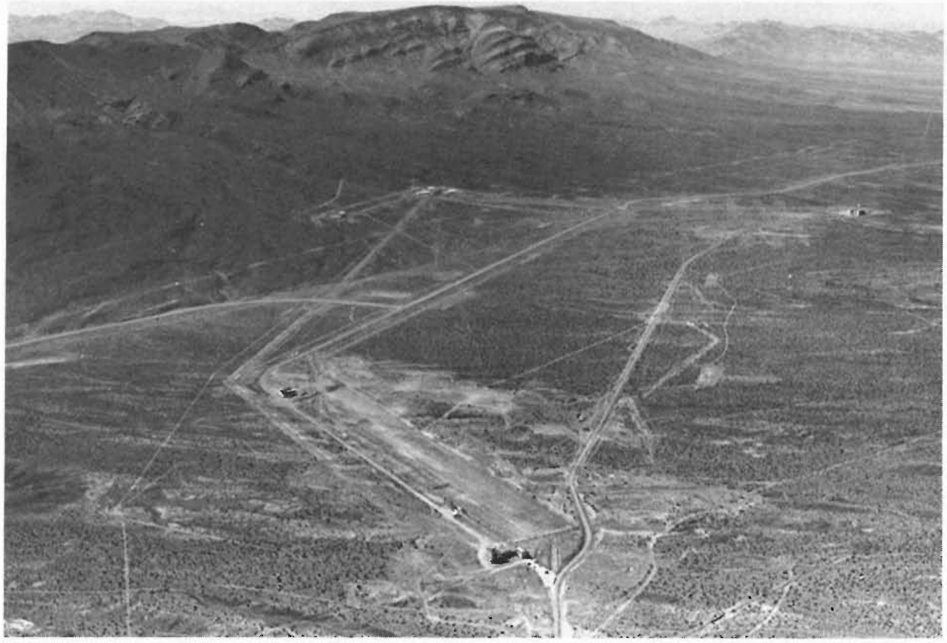


Fig. 7. A view of Wahmonie Flat, looking southwest toward Skull Mountain. Because of its favorable geology and the fact that roads, power, and some buildings are already in place, this unrestricted area within the boundaries of the Nevada Test Site is regarded as the strongest candidate for location of a National Underground Science Facility.

nique has recently been developed by G. S. Hurst and his colleagues at Oak Ridge National Laboratory. In barest outline the technique involves selective ionization of atoms of the desired element by laser pulses of the appropriate frequency. The ionized atoms can then readily be removed from the sample and directed into a mass spectrometer, where the desired isotope is counted. Repetitive application of the technique to increase the selection efficiency has been demonstrated.

The standard solar model predicts that a few atoms of krypton-81 would be produced per day in a volume of bromine solution similar to that of the chlorine solution in the Davis experiment. This is a sufficient number for successful application of resonance ionization spectroscopy. However, two other problems must be addressed. Protons produced by muons, neutrons, and alpha particles may introduce a troublesome background via the $^{81}Br(p,n)^{81}Kr$ reaction, and naturally occurring isotopes of krypton may leak into the tank of bromine solution and complicate the mass spectrometry. A complete assessment of the feasibility of the bromine-81 experiment requires use of the Homestake facility. Davis, Hurst, and their collaborators are currently establishing a group including scientists from Los Alamos to continue the chlorine experiment and to fully develop and mount the bromine experiment. A full-scale bromine experiment is about two years away.

A National Underground Science Facility

For at least two decades scientists with experiments demanding the enormous shielding from cosmic rays afforded by deep underground sites have been setting up their apparatus in working mines. We owe a great debt to the enlightened mine owners who have allowed this pursuit of knowledge to take place alongside their search for valuable minerals. However, as the experiments increase in complexity, the need for more supportive facilities becomes more obvious, and dedicated facilities are being created around the world. Several years ago Italy took advantage of the construction of a new highway tunnel in the Apennines to begin building a major underground laboratory. This Gran Sasso Laboratory will include three large experimental rooms with overburden of approximately 5000 mwe. Because of its size, depth, and ready accesss, this laboratory will be unrivaled as a site for underground experiments. European scientists are already at work planning the next generation of proton decay, solar neutrino, and cosmic-ray muon experiments to be placed there.

The Soviet Union, also, is constructing a dedicated facility to accommodate experiments on cosmic rays and solar neutrinos. The facility, located in the Baksan valley, has a horizontal entryway extending 4 kilometers (about 5000 mwe) under the Caucasus Mountains in the vicinity of Mt. Elbrus. Surface housing and laboratory space are already in place, a 460-ton cosmic-ray telescope has been in operation at a modest depth for several years, and large rooms are being built to house both a chlorine experiment (five times larger than the Homestake experiment) and a 50- to 60-ton gallium experiment.

Looking toward the day when the next generation of these searches for rare events will begin in the United States, Los Alamos has proposed construction of a National Underground Science Facility. What should such a facility be like? A theme we heard repeatedly as we sought advice was to think big initially. The entryway should be large, and the experimental area should include at least several rooms in which different experiments can be in progress simultaneously. Provisions for easy expansion, ideally not only at the principal depth but also at greater and lesser depths, should be available. Another aspect that must be carefully considered is safety. The underground environment is intrinsically hostile, and in addition some experiments may, like the Homestake experiment, involve large quantities of materials that pose hazards in enclosed spaces. Materials being considered for the bromine experiment, for example, include dibromoethane, and future proton-decay experiments being discussed involve cryogenic materials under high pressure and toxic or inflammable materials. Excellent ventilation and gas-tight entries to some areas are obvious requirements.

One argument in favor of a dedicated facility is simple but compelling: the need to have access to the experimental area controlled not by the operations of a mine or tunnel but by the schedule of the experiments themselves. Another is the need for technical support facilities adequate to experiments that will rival in complexity those mounted at major accelerators. And not to be ignored is the need for accommodations for the scientists and graduate students from many institutions who will participate in the experiments.

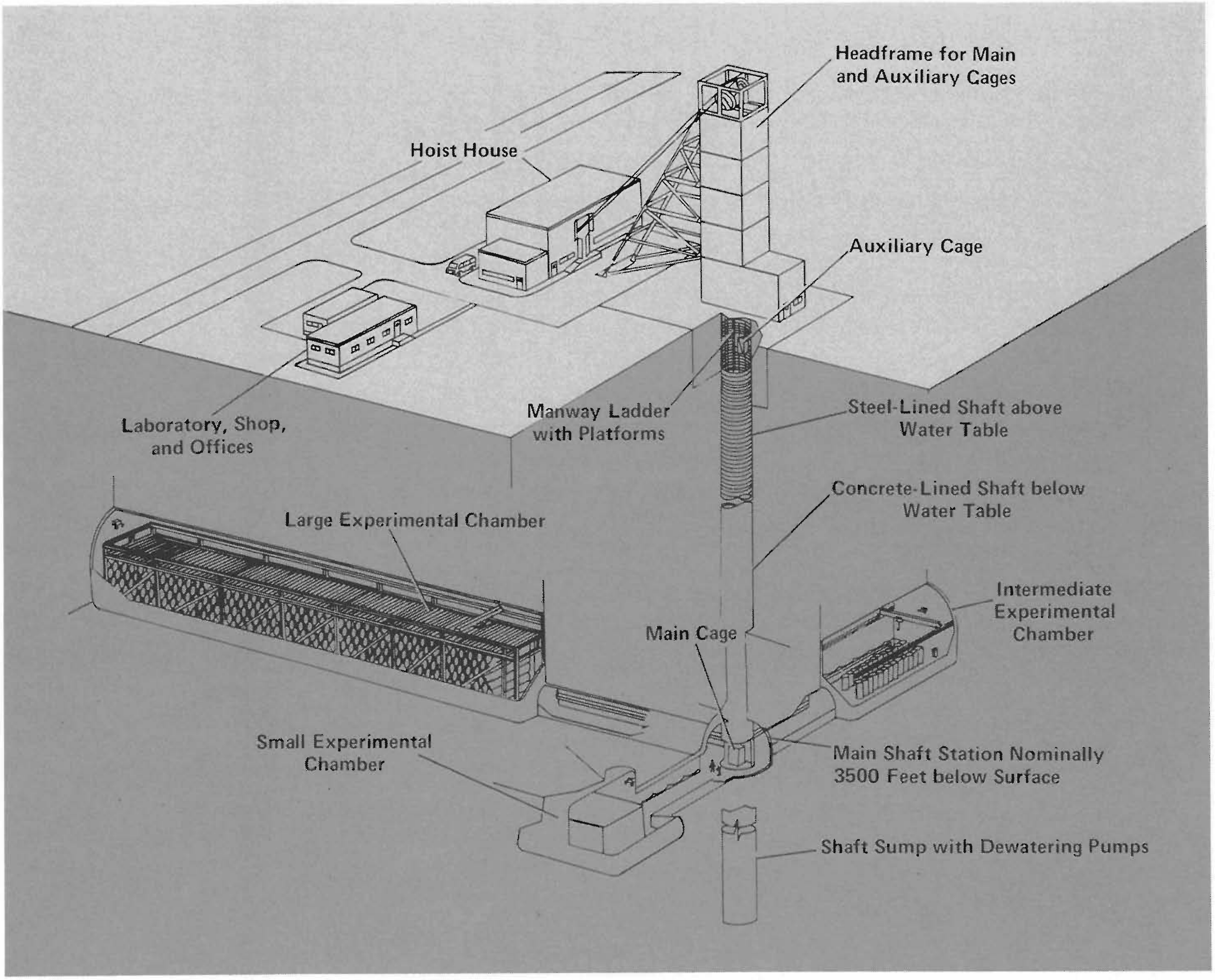


Fig. 8. Artist's conception of the National Underground Science Facility proposed by Los Alamos.

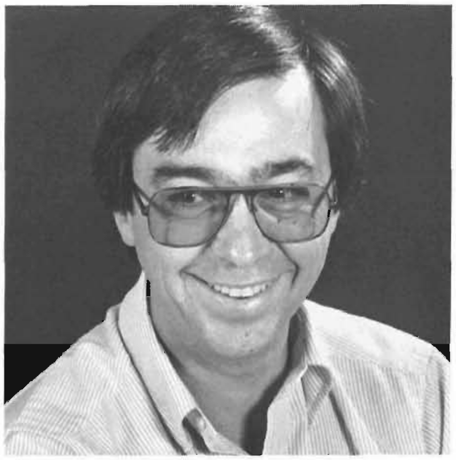
A careful search for a geologically suitable site that could be conveniently managed from Los Alamos unearthed one very strong candidate at the Department of Energy's Nevada Test Site. Extensive data for this site, located in an unrestricted portion of NTS and known as Wahmonie Flat (Fig. 7), indicate that its geology is excellent for the purpose. An additional attraction is the existence of surface buildings, power, and roads for logistic support and of facilities nearby for technical support. One commonly mentioned concern about the site—that the testing of nuclear weapons in other portions of NTS would interfere with experiments that might be mounted at the facility—is surprisingly easy to dispel with the information that seismic disturbances are typically very greatly attenuated at depth.

Guided by the results of the site survey and by extensive technical advice from members of the physics community, Los Alamos has now prepared a proposal for construction and operation of a National Underground Science Facility at NTS (Fig. 8). At present the proposal calls for a vertical entry by a 14-foot shaft extending to 3600 feet (approximately 2900 mwe), 12-foot by 12-foot connecting drifts at 3500 feet, and two chambers (40 feet by 200 feet by 46 feet and 30 feet by 50 feet by 25 feet). The shaft and hoist will be so constructed that extension to a depth of 6000 feet and addition of other chambers will be possible as the experimental program develops. This facility, assuring a site for continued American leadership in science underground, can be constructed for $50,000,000, an amount comparable to the likely cost of a single second-generation proton-decay detector.

Conclusion

We have touched in detail upon only two of the fascinating experiments that drive scientists deep underground. Such experiments are not new on the scene, but the large and sophisticated nucleon-decay detectors being planned open up a new era. These devices should not be regarded as apparatus for a single experiment but as facilities useful for a variety of observations. They may be able to monitor continuously the galaxy for rare neutrino-producing events or the sun for variations in neutrino flux and hence in energy production. The day may be approaching, as Alfred Mann is fond of saying, when we will be able, from underground laboratories, to take the sun's temperature each morning to see how our nearest star is feeling. ■

AUTHORS



L. M. Simmons, Jr., has been, for the last year and a half, an Assistant Division Leader in the Laboratory's Theoretical Division and Program Manager for the proposed National Underground Science Facility. He received a B.A. in physics from Rice University in 1959, an M.S. from Louisiana State University in 1961, and, in 1965, a Ph.D. in theoretical physics from Cornell University, where he studied under Peter Carruthers. He did postdoctoral work in elementary particle theory at the University of Minnesota and the University of Wisconsin before joining the University of Texas as Assistant Professor. In 1973 he left the University of New Hampshire, where he was Visiting Assistant Professor, to join the staff of the Laboratory's Theoretical Division Office. There he worked closely with Carruthers, as Assistant and as Associate Division Leader, to develop the division as an outstanding basic research organization while continuing his own research in particle theory and the quantum theory of coherent states. He has been, since its inception, co-editor of the University of California's "Los Alamos Series in Basic and Applied Sciences." In 1979 he originated the idea for the Center for Nonlinear Studies and was instrumental in its establishment. In 1980 he took leave, as Visiting Professor of Physics at Washington University, to work on strong-coupling field theories and their large-order behavior, returning in 1981 as Deputy Associate Director for Physics and Mathematics. While in that position, he developed an interest in underground science and began work as leader of the NUSF project. He is an Honorary Trustee of the Aspen Center for Physics and has also served that organization as Trustee and Treasurer.

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