

loop arrangement is highly stable mechanically. For hypothetical monopoles passing through the loops, about 70% of the trajectories will intersect at least two of the loops, providing coincidence information. The total area is ten times that of the flip coil. An additional factor of five in effective detecting area is gained because Cabrera also will be able to detect near-miss trajectories that do not pass through because they would cause a field change within the ultralow-field shield. Cabrera expects that the group will be taking data with the new equipment beginning this month.

Cabrera stresses that the event he has reported is "not yet a discovery. It's an interesting event. We're working hard with new apparatus to see definitively if there are such particles. It's tough to be very extravagant with only one data point. But it's also difficult to make it go away. We're caught on a knife edge."

Theory. In 1974 Gerard 't Hooft (University of Utrecht) and A. M. Polyakov (Landau Institute for Theoretical Physics, Moscow) independently showed that if you have a non-Abelian gauge group that is semisimple and that spontaneously undergoes a breakdown of scale, such theories have solutions corresponding to Dirac magnetic monopoles. They further showed that the mass of the monopole would be the characteristic scale of symmetry breaking divided by the fine-structure constant. That same year Howard Georgi, Helen Quinn and Steven Weinberg (all then at Harvard) showed that for a large class of grand unified theories, the unification scale—the region where strong, weak and electromagnetic couplings become equal—is about 10^{14} GeV. All the grand unified theory predictions for monopole mass are in the ballpark of a hundred times the unification scale, that is 10^{16} GeV.

If any monopoles exist now, presumably they would have been produced in the very early Universe, about 10^{-35} sec after the Big Bang, at a time when the unified interactions break apart into strong, weak and electromagnetic.

Cabrera cites an observational upper bound on the mass density of monopoles to be given by the local "missing mass." This limit is in the range 0.03–0.05 solar masses/cubic parsec. One can assume that because the monopoles are so massive their velocities would be no greater than about 300 km/sec (as Alvarez says, just sauntering by an atom so that little or no ionization takes place). Then Cabrera estimates that the number of monopoles passing through the Earth's surface would be $4 \times 10^{-10} \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$. Such a flux would yield 1.5 events per year through his loop.

In 1969 Eugene Parker (University of

Chicago) pointed out that if monopoles are distributed throughout the galaxy, they would leach energy out of the galactic magnetic field and soon destroy the field. Some argue that monopoles are concentrated locally, but it's difficult to produce a mechanism for this concentration. At the GUT workshop in April, Glashow mentioned an idea developed by him, Savas Dimopoulos, Edward Purcell (Harvard) and Frank Wilczek (University of California, Santa Barbara). They speculate that the monopole flux arriving on Earth originates in the Sun. Alvarez has called attention to measurements of the Sun's magnetic field for the last five "quiet periods" that once led John Wilcox (Stanford) to write a 1972 paper called, "Why does the Sun sometimes

look like a magnetic monopole?" A few months ago Alvarez calculated, assuming those measurements are correct, that the monopoles in the Sun must have masses greater than 10^{12} GeV to keep them together by gravitational attraction in spite of their mutual repulsion.

Perhaps monopoles collect at the center of the Earth, too, Alvarez speculates. You couldn't hope to put a monopole on a table and experiment with it. As Paul Frampton (University of North Carolina) points out, "Because of its enormous mass, the thing would be unimpressed by a table. Earth's gravitational pull could be greater than the electromagnetic force between a monopole and a typical atom. So the monopole would go straight through."—GBL

Hunting neutron-antineutron oscillation

When Murray Gell-Mann and Abraham Pais predicted in 1955 that the K^0 meson should exhibit an oscillating probability for metamorphosis into its antiparticle, the $\bar{K}^0$, they cited the neutron as a counterexample. The conservation of baryon number, they pointed out, would prevent the neutron-antineutron analog of neutral-kaon oscillation. But nowadays, with grand unified theories of the elementary particles very much in favor, all bets based on baryon-number conservation are off. A prodigious experimental effort (PHYSICS TODAY, January 1980, page 17) attests to the widespread expectation that proton decay will be seen with a lifetime of about 10^{31} years.

But the same SU(5) grand unified theory that predicts this finite proton lifetime does not (in its simplest form) permit neutron oscillation. The SU(5) unification of quarks and leptons in a single gauge-theoretic framework, proposed by Howard Georgi and Sheldon Glashow (both at Harvard) in 1974, replaces baryon conservation by the conservation of $B - L$, the difference between baryon and lepton number, thus forbidding $n \leftrightarrow \bar{n}$, the neutron-oscillation transition.

There are, however, rival unification theories. Robert Marshak (Virginia Polytechnic Institute) and Rabintra Mohapatra (City College of New York) have recently put forward¹ a "partial (as distinguished from grand) unification theory" based on a left-right symmetric electroweak scheme which, when joined to the usual color-SU(3) group of quantum chromodynamics, yields a color-SU(4) group structure mathematically similar to an earlier proposal of Jogesh Pati (University of Maryland) and Abdus Salam (International Centre for Theoretical Physics, Trieste, and Imperial College, London).

In contrast to the SU(5) grand unification, the Marshak-Mohapatra theory predicts neutron oscillation on a time scale that may well be accessible to experiment. Proton decay, on the other hand, is not permitted in the Marshak-Mohapatra partial unification scheme.

One could complicate the spontaneous-symmetry-breaking mechanism in the SU(5) theory to get neutron oscillations at an observable level. But such departures from "minimal SU(5)" would deprive the theory of much of its simple elegance, Georgi contends. "I would be greatly surprised if we find neutron oscillation," he told us. "But if we do, it will be most instructive."

Aesthetic prejudices notwithstanding, Lay-nam Chang (Virginia Polytechnic Institute) and Ngee-pong Chang (City College of New York) have proposed² a modification of SU(5) that would permit both neutron oscillation and proton decay at observable levels by extending the theory's minimal symmetry-breaking mechanism to include Higgs bosons with masses around 10^4 or 10^5 GeV.

Because neutron oscillation plays such a central role in choosing among competing unification theories, a number of experimental attempts to look for this exotic phenomenon are now in various stages of planning, and one group has recently announced preliminary results. At the International Conference on Baryon Nonconservation, held in Bombay in January, Milla Baldo-Ceolin (University of Padua) reported the first results obtained by a CERN, Laue-Langevin, Padua, Ruth-erford, Sussex collaboration using the cold-neutron facilities of the Laue-Langevin Institute at Grenoble. Their first null finding—that the characteristic neutron oscillation time is greater than

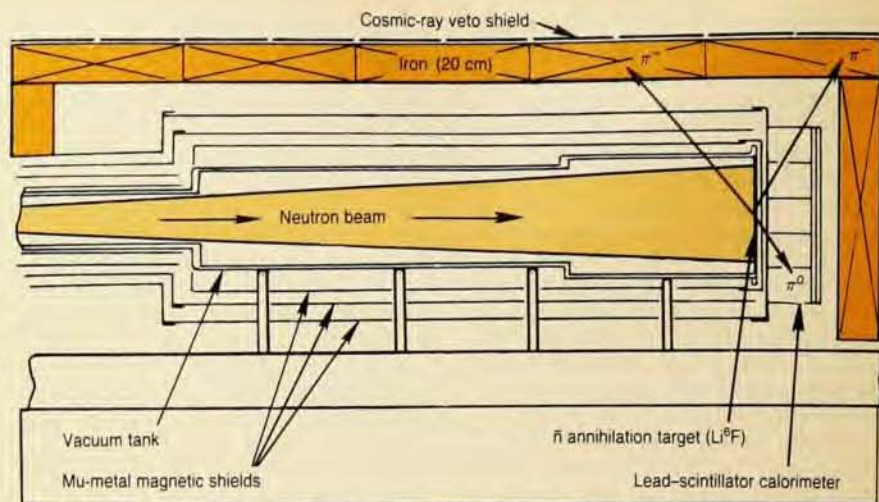
10^5 seconds—is not in itself very newsworthy. One knows as much from the observed stability of nuclei against $\Delta B = 2$ decays. But the Grenoble group expects eventually to achieve a sensitivity limit of 3×10^8 seconds—within the range of oscillation times predicted by the Marshak-Mohapatra and Chang theories.

Quite apart from the details of any particular unification theory, the discovery of neutron oscillation on a time scale of 10^6 to 10^9 sec would imply the onset of “new physics” somewhere in the energy region between 10^2 and 10^6 GeV. This is to be contrasted with the “desert,” devoid of new thresholds between 10^2 and 10^{15} GeV, implied by minimal SU(5).

Phenomenology. If a coupling does exist that permits the $\Delta B = 2$ oscillation between neutron and antineutron, the mass eigenstates would be $n + \bar{n}$ and $n - \bar{n}$, just as in the Gell-Mann-Pais scheme for neutral kaons. The off-diagonal element of the neutron mass matrix, the difference Δm between these two mass eigenvalues, would be the measure of the strength of the neutron-antineutron coupling; its reciprocal is the characteristic oscillation time $\tau_{n\bar{n}}$. If the mass difference vanishes, there is no neutron-antineutron coupling and hence no oscillation.

A free neutron in a pure n state at time $t = 0$ would, in the absence of any external field, have a time-oscillating transition probability to the $\bar{n}$ state given by $\sin^2(t/\tau_{n\bar{n}})$. The Marshak-Mohapatra and Chang theories yield estimates of 10^7 seconds for $\tau_{n\bar{n}}$, give or take an order of magnitude, corresponding to a Δm of about 10^{-23} electron volts. The experimental observing time for a single neutron is of course much shorter than this, so that the transition probability is well approximated by $(t/\tau_{n\bar{n}})^2$. For a neutron inside a nucleus, the rapid oscillation introduced by the large difference between the interaction energies of the n and $\bar{n}$ states in the (hadronic) nuclear field completely destroys the coherence of the transition amplitude's growth; the probability of finding an antineutron grows only linearly with time. In fact, a free-neutron $\tau_{n\bar{n}}$ of 10^7 seconds translates into a nuclear decay time of about 10^{30} years! Because we already know that nuclei are stable for at least 10^{30} years against $\Delta B = 2$ decay, we already had a lower limit longer than 10^6 seconds for $\tau_{n\bar{n}}$ before the first Grenoble result.

Even outside of a nucleus, the neutron is still not really free. The Earth's magnetic field introduces an energy splitting between neutron and antineutron ($\Delta E \approx 10^{-11}$ eV) that would destroy the transition coherence sufficiently to make neutron oscillation unobservable. But happily it turns out that one



The first-phase Laue-Langevin search for neutron-antineutron oscillation. After traversing an 8-meter path shielded against the Earth's magnetic field, the neutron beam strikes a target behind which a calorimeter is placed to detect the energy released in an $n\bar{n}$ annihilation.

need only shield the Earth's field by about a factor of 10^3 —a relatively easy task. The condition for maintaining the coherence of the neutron oscillation is that $t\Delta E$, where t is the total time available for observing a single neutron, must be much less than unity. For thermal or liquid-deuterium-cooled neutrons observed over a drift path of a few tens of meters, a residual magnetic field of 10^{-3} gauss will have a negligible effect on the transition probability.

The Grenoble experiment avails itself of the high neutron flux of the 57-megawatt Laue-Langevin Institute reactor and the Institute's unique cold-neutron facilities (PHYSICS TODAY, June 1980, page 21). In the recently completed first phase of the experiment, a beam of 10^9 neutrons per second, cooled to 25 K by reflection off liquid deuterium, traversed an 8-meter path magnetically shielded from the Earth's field by a triple mu-metal shield. By using cold rather than thermal neutrons one increases their transit time by about a factor of three, thus achieving a tenfold increase in sensitivity. At the end of the path, the beam was run into a target covered by a calorimeter system designed to detect the energy released when an antineutron annihilates in the target.

A finite $\tau_{n\bar{n}}$ would be measured by the fraction of neutrons transformed into antineutrons during the 8-meter magnetically shielded traversal. The unshielded portions of the path from reactor to target would contribute negligibly to the transition probability. The target was surrounded by anti-coincidence counters to veto cosmic-ray background that might mimic $n\bar{n}$ annihilation events. In 15 days of running, 687 $n\bar{n}$ annihilation event candidates were collected. But after comparing this total with background rates measured by running with the reactor off or

with a suppressing magnetic field imposed, the group concluded that these candidates were all attributable to cosmic-ray background. Thus they quote a lower limit of 10^5 seconds for $\tau_{n\bar{n}}$.

The Grenoble collaboration hopes ultimately to achieve a sensitivity of 10^8 or 10^9 seconds. The group has recently completed the construction of a new annihilation detector system with higher spatial resolution and larger solid-angle coverage. This should “drastically” reduce the cosmic-ray background, Baldo-Ceolin told the Bombay meeting, while increasing the $\bar{n}$ detection efficiency. A new cold-neutron source is now being installed at the Laue-Langevin reactor. With the higher flux this source will provide and a longer shielded path of 30 meters, Baldo-Ceolin estimates that a running time of six months should yield a sensitivity of about 3×10^8 seconds.

Competing unification theories. It is important to look for neutron oscillation, Marshak told us, because minimal SU(5) has run into a number of difficulties during the past year. The estimate of the proton lifetime depends sensitively on the quantum-chromodynamic parameter Λ , which sets the scale for QCD couplings. Recent upsi-decay and neutrino scattering experiments have lowered the best estimate of Λ —by perhaps as much as a factor of four. This would reduce the minimal-SU(5) calculation of the proton lifetime below 10^{30} years, bringing it into conflict with experimental limits already attained by the Kolar gold-mine experiment in India and Kenneth Lande's results at the Homestake gold mine in South Dakota. (The much larger proton-decay experiments of the Irvine-Michigan-Brookhaven and Harvard-Purdue-Wisconsin collaborations have not yet produced any results.) Georgi concedes that “evidence is piling up to the

point where you have to push all the uncertainties in one direction to be consistent with experiment; but," he cautions, "we don't really know how to calculate all that well in QCD."

Marshak also stresses the question of the neutrino mass. Examining the end point of the tritium beta-decay spectrum, a group at the Institute for Theoretical and Experimental Physics (Moscow) concluded that the electron neutrino has a mass of a few tens of electrons volts (PHYSICS TODAY, July 1981, page 17). While minimal SU(5) assumes massless neutrinos, Mohapatra and Goran Senjanovic (Brookhaven) have shown³ that the left-right symmetric theory predicts two neutrinos of nonvanishing mass—one light, one heavy—for each quark generation. (Each of these neutrinos is its own antiparticle.) The light electron neutrino in the left-right symmetric theory would be responsible for left-handed weak couplings. Its predicted mass is roughly in the range of the Soviet experimental result. The neutrinos responsible for right-handed couplings are much heavier in this theory, thus breaking the left-right symmetry of the underlying gauge-group structure and explaining the parity violation observed in low-energy weak interactions. Georgi counters that one can easily fix up SU(5) in nonessential ways to generate a small neutrino mass. "The only puzzle—if the Russians are right—is that the neutrino mass is so large," he told us. "We would have expected a mass of less than 1 eV."

Marshak and Mohapatra describe their scheme as a *partial* unification theory because it still requires two independent coupling constants for the electroweak and strong-interaction pieces of the theory. Grand unification theories such as SU(5), by contrast, attempt to make do with a single coupling constant for all interactions except gravity (PHYSICS TODAY, September 1980, page 30). So ambitious a unification has the astonishing—Marshak would say implausible—consequence that there is no new physics between 10^2 GeV (the mass of the gauge bosons, $W^\pm$ and Z^0), that break the electroweak symmetry) and 10^{15} GeV (the mass of the grand-unification gauge bosons).

The Marshak-Mohapatra theory would populate this desert by introducing a new symmetry-breaking intermediate mass scale around 10^6 GeV. Their theory replaces the group structure $SU_{\text{left}}(2) \times U(1)$ of the standard Weinberg-Salam-Glashow electroweak theory by the left-right symmetric structure $SU_L(2) \times SU_R(2) \times U(1)$. The right handed (R) components of the quarks and leptons are treated just like their left-handed (L) counterparts—as SU(2) weak isodoublets. This formal left-right symmetry is broken by the

fact that the right-handed analogs of the weak vector bosons ($W_R^\pm, Z^0$) are supposed to be about three times as heavy as $W_L^\pm$ and Z^0 . An appealing feature of this scheme, Marshak stresses, is that it renders the physical interpretation of the U(1) hypercharge group unambiguous. The weak hypercharge becomes $B-L$ for both left- and right-handed leptons.

This identification of the weak hypercharge permits $B-L$ to become a local gauge-invariant symmetry. Thus, unlike the global $B-L$ symmetry of the standard theory, it can be spontaneously broken to permit neutrino oscillation. When $SU_L(2) \times SU_R(2) \times U(1)$ is joined with the color-SU(3) group of the strong interactions, the Marshak-Mohapatra partial unification yields the group $SU_L(2) \times SU_R(2) \times SU_{\text{color}}(3)$, where $B-L$ becomes the fourth color. The mass scale for this partial unification is estimated to be about 10^6 GeV. Below this energy both parity and $B-L$ conservation are spontaneously broken. Grand unification in this scheme, Marshak told us, might have to await extrapolation to the Planck mass (10^{19} GeV, where the Compton wavelength becomes equal to the Schwarzschild radius.) At this energy, gravity would also have to be taken into consideration.

Other experimental searches for neutron oscillation are being planned and proposed. An Oak Ridge, Harvard, University of Tennessee collaboration proposes to use thermal neutrons from the Oak Ridge Research Reactor to achieve a sensitivity of 2×10^8 seconds for τ_{nn} in a 120-day run. Richard Wilson (Harvard) explained to us that the use of thermal rather than cold neutrons is more than compensated by the fact that the Oak Ridge reactor

produces a much higher total neutron intensity than one can get at Grenoble. "In a year of running we would get a full mole of neutrons," Wilson told us. The collaboration, led by Glenn Young and Tony Gabriel (Oak Ridge), William Bugg (University of Tennessee) and Wilson and Matt Goodman (Harvard), has already tested the detector components in a beam at the smaller Oak Ridge TSF reactor, configured to simulate the environment expected at the Research Reactor.

An Italian group led by Sergio Ratti is undertaking an experiment with the 4-megawatt University of Padua reactor. Two experiments are under discussion for Los Alamos: Richard Ellis plans to use the Los Alamos Meson Physics Facility as a pulsed neutron source, while Herbert Anderson is considering the Los Alamos reactor for a neutron oscillation search. Hajimi Yoshiki and his colleagues at KEK, near Tokyo, have suggested an experiment to look for antineutrons generated among ultracold neutrons, which can be stored in a "bottle" for as long as they live (about 10^3 seconds).

These experiments point up an interesting trend in the physics of elementary particles. Exotic predictions generated by the theoretical quest for ultrahigh-energy unification are more and more being addressed by low-energy techniques that do not require large accelerators.

—BMS

References

1. R. E. Marshak, R. N. Mohapatra, Phys. Lett. **91B**, 222 (1980); R. N. Mohapatra, R. E. Marshak, Phys. Rev. Lett. **44**, 1316 (1980).
2. L. N. Chang, N. P. Chang, Phys. Lett. **92B**, 103 (1980).
3. R. N. Mohapatra, G. Senjanovic, Phys. Rev. Lett. **44**, 912 (1980).

Livermore flash-radiography facility

The 100-foot-long electron linac at right is the heart of the new High Explosive Flash Radiography Facility at Livermore. Dedicated in April, the Facility is intended primarily for weapons experiments. It provides extremely intense, ultrashort bursts of highly penetrating x-ray photons— 3×10^{11} four-to-five-MeV photons in 60-nanosecond pulses. Thus it will render high-time-resolution x-ray pictures of the deformation of interior components of nuclear-warhead mockups during the detonation of their conventional explosives. The requirement that such implosions maintain a high degree of spherical symmetry leads to very demanding tolerances on the weapons components. The x-ray flash is produced by a 4-kA beam of 20-MeV electrons. The accelerator is a ferrite-core induction linac. □

