cussed studying time-dependent properties such as persistent currents to make sure we understood why the Meissner effect was so small." But the news from Boston spread fast. In the last week of December, several groups from around the world reported that the critical temperature for superconductivity in the oxide studied by Bednorz and Müller could be raised to about 40 K by replacing barium with strontium. And Chu stunned the world of physical sciences with his announcement on 16 February that he and his collaborators had obtained superconductivity above 90 K in an oxide material. Chu's paper reporting the discovery was received at the editorial office of *Physical Review Letters* on 6 February; he announced the discovery, he told us, only after the paper was accepted for publication. Chinese and Japanese physicists announced in the last week of February that they had independently discovered superconductivity above 90 K. As a result of these developments, a hastily arranged special session on the new superconductors at the annual March meeting of The American Physical Society in New York turned into a historic occasion and was dubbed the "Woodstock of physics." The theme song at this Woodstock was one–two–three, after the chemical composition $RBa_2Cu_3O_{7-y}$, where R is a rare earth element, of the materials with T_c above 90 K. (See PHYSICS TODAY, April 1987, page 17.)

Several chapters in standard textbooks in solid-state physics may have to be rewritten when the properties of the new superconducting oxides and the mechanism of superconductivity in them are properly understood. Many theorists have proposed novel mechanisms for superconductivity in the oxides because they believe that phonon-mediated pairing of electrons cannot give critical temperatures as high as 90 K. The critical temperature of the 90-K materials changes negligibly with the isotopic mass of the various elements. (See PHYSICS TODAY, July, page 17.) Theorists regard this lack of the isotope effect as evidence that pairing of electrons in the oxide superconductors is mediated by an electronic or magnetic excitation and not by phonons. We asked Bednorz and Müller how high they thought they could raise the critical temperature when they set out on their search and whether any of the limits that theorists have discussed on how high the T_c can be in the phonon mechanism in any way discouraged them in their research. Müller related an anecdote in reply. During his sabbatical at IBM Yorktown Heights (1978–80), he said, he collaborated with Melvin Pomerantz on an experiment on microwave absorption in thin films of granular aluminum. The critical temperature of the films, composed of small, oxide-coated grains of aluminum, was about two times that of pure aluminum which has a T_c of 1.1 K. Müller found that very interesting and wondered whether a similar enhancement in T_c could be obtained in metallic superconductors whose critical temperatures were already in the 10–15-K range. But the theorists told him that because of its low T_c, aluminum is described by the weak-coupling BCS theory, but that the enhancement was not possible in superconductors with T_c of 10–15 K, which are better described by the so-called strong-coupling theory. "After I heard this," Müller said, "I decided not to listen to theorists anymore."

How much longer would Bednorz and Müller have continued their search if they had not discovered superconductivity in January 1986? "We were quite persistent," both the laureates smiled and said. What was the next combination on their list? Did they have a list? "We had a list, and we still have one in the lab. Maybe we will meet each other again in a few years and I will then tell you more about our list," Bednorz said. Details of the three-year search at IBM Zurich, it seems, will provide grist for the mill of historians and sociologists of science for many years.

Müller got his master's and doctoral degrees in physics at the Swiss Federal Institute of Technology (ETH) in Zurich in 1952 and 1958. He was a staff member at the physics department of ETH from 1952 to 1958. He was next a project manager at the Batelle Institute, Geneva, from 1959 to 1963. Müller was appointed as a lecturer at the University of Zurich in 1962 and was made Titular Professor in 1970. He joined the IBM Zurich Research Laboratory as a research staff member in 1963, managed its physics department from 1972 to 1985, and has been an IBM Fellow since 1982. "It is very satisfying that our work has generated so much interest and has been recognized by the Swedish committee," Müller said about winning the Nobel Prize less than a year after his work with Bednorz was accepted by their colleagues. "We never thought about the prize," he added. "We only wanted to go beyond the intermetallic A15 compounds."

Bednorz got his undergraduate degree at the University of Münster in 1976 and his doctorate at ETH in 1982. He did research for his PhD thesis at IBM Zurich under Müller's supervision. He has been a research staff member at IBM Zurich since 1982. "It is hard to describe," he said when we asked him about what it feels like to win the Nobel Prize. "I have to look at myself.... I have to learn," he added.

—ANIL KHURANA

Reference

1. For a summary of major developments in superconducting materials in the past two decades, see, for example, M. R. Beasley, T. H. Geballe, PHYSICS TODAY, October 1984, p. 60.

TWO-NEUTRINO DOUBLE β-DECAY SEEN; NEUTRINOLESS DECAY SOUGHT

Many nuclei with even numbers of protons and neutrons can undergo double beta decay, emitting two electrons and two neutrinos, but the halflife for this process is so long that it had been deduced until recently only by measuring the abundance of daughter nuclei from double beta decay of elements in geologic materials. Now Steven Elliott, Alan Hahn and Michael Moe of the University of California at Irvine have observed the double beta decay of selenium-82 in their laboratory and determined its halflife to be $1.1^{+0.8}_{-0.3}\times10^{20}$ years,[1] a time interval that is orders of magnitude longer than any previously detected in a laboratory. Besides being a feat in its own right, the Irvine measurement is a milestone en route to a more elusive goal—observation of a double beta decay in which two electrons but *no* neutrinos emerge. This neutrinoless decay, which proceeds by the exchange of a virtual neutrino between the two neutrons, can occur only if neutrinos have mass. It is strictly forbidden by the standard theory of electroweak interactions but is predicted as a manifestation of the small symmetry breaking that arises in some grand unified field theories.

The Irvine measurement of a two neutrino double beta decay rate gives hope that future experiments may be sensitive even to very low rates for the neutrinoless double beta decay. It also provides the first direct calibration of the nuclear model calculations that must be used to relate any observed rates of neutrinoless beta decay to limits on the effective neutrino mass.

Measurement of the decay rate

The few electrons from the rare two-neutrino double beta decay are easily hidden in the background of electrons from other events because the distribution of their combined energy is a broad spectrum rather than a sharp peak: The electrons must share the total energy with the unobserved neutrinos. The Irvine team has worked for many years to understand and, where possible, eliminate the background.

Moe and his colleagues used a time projection chamber, described by Hahn as a "glorified drift chamber." The sample of 14 grams of 97%-enriched Se^{82} (on loan from Oak Ridge National Laboratory) is sandwiched between two pieces of Mylar foil and placed in the central plane of the chamber, which is filled with a mixture of helium and propane gas. An electric field is maintained between the sample and planes of grid wires on either side. The chamber is surrounded by a thick lead shield and by proportional counters to veto events associated with cosmic rays. The entire chamber is placed in a 700-gauss magnetic field.

Electrons from the selenium decay describe a helical path in the magnetic field, and ionize atoms of the gas along the path. These ionization electrons drift toward the grid wires, and orthogonal sets of anode and cathode wires register their xy coordinates with 5-mm resolution. The inital z coordinate of the ionization electron is deduced with the same 5-mm resolution from its arrival time at the grid. The loci of these ionization electrons trace the path of the decay electron.

One troublesome source of background electron pairs is the decay of bismuth-214, an isotope in the uranium decay series. The beta decay of this isotope is sometimes followed by internal conversion in which the excited daughter nucleus (polonium-214) drops to its ground state by kicking out an orbital electron. The net result is production of two electrons that could be confused with those from double beta decay. However, the time projection chamber can distinguish these spurious Bi^{214} events by sensing the alpha particle from the 164-microsecond decay of Po^{214}. In a similar way, the experimenters distinguish Bi^{212} from the thorium series, and they use the rates of both bismuth decays to estimate the decays of other isotopes in their respective chains. Moe told us that at one point they suspected that the bismuth came from radon in the wires in their chamber, but they now know that it comes from the gas cylinders in which they buy their helium. They are working to eliminate this contamination in the future.

Background electron pairs also stem from cosmic rays: A gamma ray of cosmic origin produces a Compton electron by scattering off the source, and that electron subsequently knocks a selenium orbital electron into the gas. The experimenters reduced the background from such Möeller scattering by excluding all events except those in which the two electrons each have an energy above 150 keV. The primary sources of background in the energy region above this cut are the remaining Möeller scattering events and the beta decay of thallium-208 follwed by internal conversion. The Irvine group fit its data to a mixture of these background sources and the two-neutrino double beta decay. After 7960 hours of live run time, the best fit (at a 68% confidence level) corresponded to 36 double beta decay events. The fit included the distribution of opening angles, which are expected to be different for the three event types. (See the figure on page 21.)

The determination of Se^{82} halflife from the Irvine time projection chamber is consistent with estimates based on geochemical and cosmochemical evidence[2,3,4] and boosts confidence in geochemical estimates of double beta decay lifetimes for other elements. To make these estimates, researchers examine ores (or meteorites) that are a few hundred million to a billion years old and rich in the isotope expected to undergo double beta decay. By extracting and measuring the quantity of the daughter nuclei present, the researchers can estimate the decay rate of the parent. Because the halflives for double beta decay are so long, the technique has only been successful for noble gas daughter nuclei, whose natural abundances in ores are so low that the isotopic anomalies produced by double beta decay are measurable. Naturally, this method is uncertain to the extent that the geological history of the ore is unknown. Furthermore, it cannot distinguish between two-neutrino and neutrinoless beta decays.

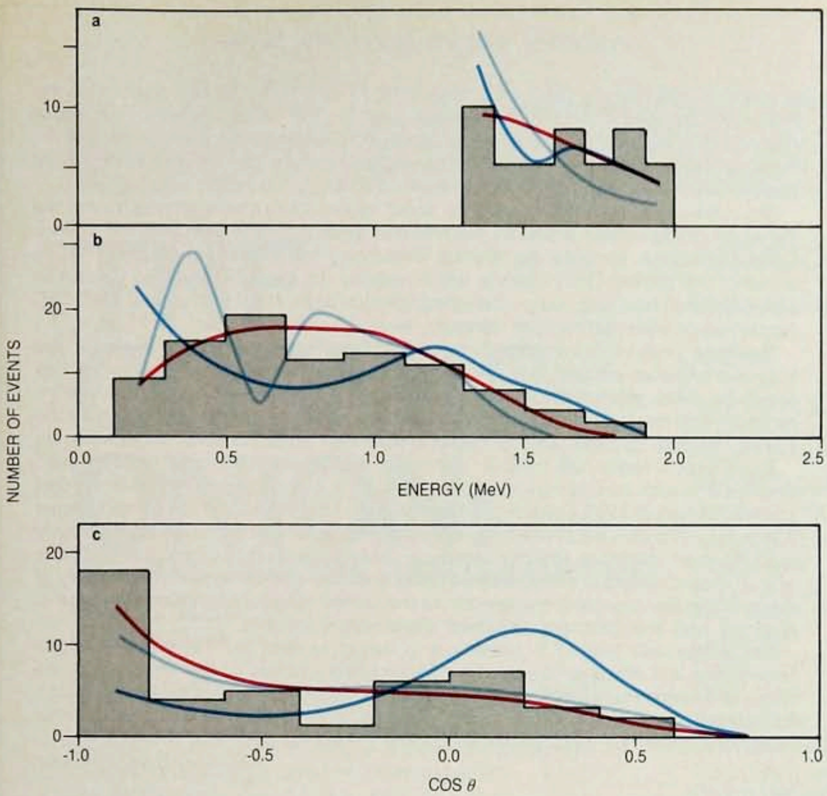
Predictions of nuclear physics

The Se^{82} halflife provides the first laboratory test of nuclear structure calculations used to predict the rates of double beta decay. Shell model calculations have tended to predict decay rates for some elements that are faster than those measured by geochemical means. Wick Haxton (University of Washington) and Jerry Stephenson (Los Alamos National Lab) have performed[5] a series of shell model calculations of both the two-neutrino and neutrinoless processes, using a realistic interaction derived from nucleon–nucleon scattering data and an effective axial vector coupling taken from single-beta decay measurements. The shell model nuclear matrix element for the Se^{82} double beta decay is 1.3 times greater than that derived from the measurement of the Irvine group, and the matrix element for calcium-48 agrees with the stringent limit set on it by a 1970 experiment at Columbia University. However, the predicted rate for the tellurium-130 decay is from 16 to 59 times faster than the rate determined by geochemical methods. A calculation based on the interacting boson model yielded similar results[6] for Te^{130}. The apparent suppression of this Te^{130} decay has puzzled nuclear theorists and made them wonder whether rates for neutrinoless double beta decays are suppressed as well.

The amplitude for double beta decay should simply be the product of single-beta-decay Hamiltonians connecting first the ground state with an intermediate state and then the intermediate state with the final state. However, the actual calculations quickly become formidable for nuclei larger than selenium, and it is necessary to truncate the number of multiparticle states included in the model. Some theorists have tried alternate approaches to simplify the many-body problem: They represent the nuclear interaction in a more schematic way than the shell model and include many fewer multiparticle states, but are then able to include more kinds of excitations.

One such technique used by several groups is called the quasiparticle random-phase approximation. These groups represent the dominant nuclear operator by the scalar products of spin operators of the two neutrons multiplied by the two isospin raising operators that transform neutrons into protons, and sum over all neutron–proton pairs. Their basis includes only those configurations achieved by replacing one neutron with one proton or vice versa.

Petr Vogel and Martin Zirnbauer of Caltech added to the quasiparticle random-phase approximation a particle–particle force relating to the spin–



Double beta decay in selenium-82 was detected from fits to measured properties of two-electron events. Shown here are the energy spectra of the two electrons (**a**) and of the individual electrons after imposition of a cutoff below 150 keV (**b**), and the distribution of the opening angles of two-electron events (**c**). Superimposed on the histograms are curves for double beta decay (red) and two possible background sources: Möeller scattering (dark blue) and the beta decay of thallium-208 followed by internal conversion (light blue).

isospin interaction,[7] and found that the nuclear matrix elements they calculate for double beta decays are very sensitive to its strength, which is adjustable. Klaus Grotz and Hans Klapdor (Max Planck Institute, Heidelberg) have calculated two-neutrino double beta decay rates with a random-phase approximation that includes both schematic spin–isospin and quadrupole–quadrupole interactions.[8] Recently, Oswaldo Civitarese (University of La Plata, Argentina), together with Amand Faessler and Tashiaki Tomoda of the University of Tübingen, used a realistic nucleon–nucleon force and, without adjusting parameters, found that they could understand quantitatively the reduction of the two-neutrino double beta decay probability.[9] This result has in the meantime been corroborated by Klapdor and his colleague Kazuo Muto, who fix the strength of the particle–particle force from experimental values for the usual single beta-plus decay.

These three theoretical groups now calculate lifetimes that are more consistent with measured values of the Te^{130} lifetime than are those from the shell model calculations. However, the predicted lifetimes are disconcertingly sensitive to the strength of the particle–paticle interactions.

Theorists are very anxious to know whether the extreme sensitivity to parameter values seen in quasiparticle random-phase approximations carries over to predictions of the neutrinoless double beta decay lifetimes as well. The answers to that question are mixed, with Vogel and Zirnbauer, in collaboration with Jonathan Engel (Caltech), answering yes, and the German groups reporting no. A clear picture still must emerge if one is to be able to sort out whether neutrinoless double beta decay is suppressed by nuclear effects or by the symmetries of particle physics.

Some additional data for evaluating these nuclear models may be generated by experiments now under way to detect the double beta decays of molybdenum, xenon and germanium. Preliminary results on a Mo^{100} experiment being conducted by a collaboration among researchers at Lawrence Berkeley Laboratory, Mount Holyoke College and the University of New Mexico indicate a lower limit on the Mo^{100} lifetime of 5×10^{18} years. This limit lies within the range of calculated values, which vary widely due to the sensitivity of the calculated Mo^{100} lifetimes to model parameters.

Neutrinoless double beta decay

Physicists have recognized for nearly 50 years that two-neutrino double beta decay is an allowed, second-order nuclear transition but that neutrinoless double beta decay would violate the conservation of lepton number. Wendell Furry first suggested in 1939 that the occurrence of neutrinoless double beta decay would imply that the neutrino was its own antiparticle, and would hence confirm the symmetrical theory of the neutrino proposed by Ettore Majorana in 1937. If the neutrino from a negative beta decay is identical to that from a positive beta decay, it would be called a Majorana particle. In that case, a Majorana neutrino ν_M from the decay of one neutron could initiate the decay of a second, as follows:

$$n \to p + e^- + \nu_M$$
$$\nu_M + n \to p + e^-$$

The double decay can proceed more rapidly if mediated by virtual neutrinos. If, however, the neutrinos are Dirac particles, that is, if the neutrino and antineutrino are distinct, the decay sequence above would be forbidden.

At first glance, then, the neutrinoless beta decay should distinguish whether neutrinos are Majorana or Dirac particles. A spate of experiments around 1950 tried to detect this neutrinoless double beta decay, whose rate was then predicted to be several orders of magnitude greater than that for the two-neutrino decay because of the greater available phase space. With the discovery that beta decay manifests a maximal violation of parity conservation, it is now recognized that the neutrino from the decay of one neutron has the wrong helicity to initiate the decay of a second neutron. Thus neutrinoless double beta decay is forbidden, whether or not the neutrino is a Majorana particle—provided the neutrino has no mass. The standard model of electroweak interactions assumes that neutrinos are massless and thus strictly forbids neutrinoless double beta decay. However, grand unified field theories predict slight violations of the conservation of baryon and lepton numbers (which are essentially only empirical conservation numbers), and suggest that the neutrino may be a massive Majorana particle. Theorists would thus welcome the observation of neutrinoless double beta decay as confirmation that at least one neutrino does have mass and as evidence for the validity of some of the extensions of the standard model. A measurement of the halflife for the decay would imply a value for the effective neutrino mass. Boris Kayser (NSF), Sergei Petcov (Bulgarian Academy of Sciences) and Peter Rosen (Los Alamos) have shown that at least one neutrino must have a mass larger than this effective mass. Kayser discussed this work at a June 1986 international symposium on nuclear beta decays and neutrinos held in Osaka, Japan.

Another possible mode for neutrinoless double beta decay would be one in which two electrons are accompanied by a massless Goldstone boson, called a majoron. A Goldstone boson is a particle generated by the breaking of a global symmetry. In this case, the majoron would be generated by the nonconservation of baryon-minus-lepton number. If the majoron appeared in this decay, it would be identified with one of a triplet of Higgs bosons. Graciela Gelmini (University of Trieste) and Marco Roncadelli first suggested the existence of the majoron, while Howard Georgi and Sheldon Glashow (both of Harvard) together with Schmuel Nussinov (Tel Aviv University) subsequently but independently predicted it and discussed its connection to beta decay.

The hunt continues

Moe and his colleagues are searching for the neutrinoless as well as two neutrino decay, as their chamber can detect both decay modes. However, the most sensitive neutrinoless experiments use germanium dectectors, which contain their own source (germanium-76) and feature higher energy resolution than a time projection chamber. Unlike the signal for the two-neutrino decay, that from the neutrinoless double beta decay would feature a sharp spike in the total energy of the two electrons around 2 MeV. So far the experiments have only managed to establish lower limits for the halflife of this decay, which are on the order of 10^{24} years. To eliminate the perennially troublesome background, researchers are fabricating crystals from virgin material obtained deep underground, where it has not been exposed to cosmic rays. They are burying these counters in mines and tunnels, and replacing other contaminated components with material of better quality.

Last January, Frank Avignone (University of South Carolina), Ronald Brodzinski, Harry Miley and Jim Reeves (all of Pacific Northwest Laboratory) created a stir at a meeting of the APS division of particles and fields when they reported a bump in their data suggestive of a possible neutrinoless double beta decay accompanied by a majoron. Many experiments have since looked for the same bump. Two experiments using germanium counters—one performed by collaborators from Caltech, the University of Neuchatel and the Swiss Institute for Nuclear Physics,[10] and the other conducted by a team from the University of California, Santa Barbara, and Lawrence Berkeley Laboratory[11]—have published results excluding majoron decay at a high degree of confidence. The Irvine group has also looked[12] unsuccessfully for the majoron decay mode in Se^{82}, but the procedure for extrapolating these results to germanium is tricky. Avignone told us that, although he and his colleagues have continued to see the bump in subsequent data, they will not be convinced until they see it in another crystal.

—Barbara Goss Levi

Palomar Begins New Sky Survey

A team of astronomers at Caltech headed by Gerry Neugebauer, director of the Palomar Observatory, has begun a five-year project to photograph the entire northern sky. Thanks to improved photographic techniques the new survey will achieve higher resolution and detect fainter objects than did the first Palomar sky survey, which was conducted in the early 1950s.

The survey will ultimately consist of 2682 square glass photographic plates 14 inches on a side—three plates for each of 894 fields of sky—taken with the 48-inch Oschin Telescope, formerly the Schmidt Telescope. The telescope was renamed in honor of the Samuel Oschin family, which recently donated \$1 million to Caltech to support research in astronomy. The telescope has been fitted with a new \$380 000 cemented-doublet achromatic corrector lens.

The three plates that cover each 6.6°×6.6° field have spectral sensitivities in the blue, red and near-infrared, and are treated prior to exposure to further increase their sensitivity. Each plate is exposed for about one hour. Neugebauer and his team estimate that they will have to make two plates for every one finally chosen for the survey, because of plate defects, airplane trails and other observational problems.

The Caltech team will initially examine the plates in search of short-lived phenomena such as supernovae and variable stars, as well as orbiting asteroids and comets. In August 1986 Caltech graduate student Christine Wilson discovered Comet Wilson in such a first-look procedure. In addition to serving as a basic atlas, the survey will help astronomers to identify previously undetected quasars, galaxies and stars, and to map changes in the positions of stars since the last survey. A similar survey of the southern sky is nearing completion at the United Kingdom Schmidt Telescope in Australia and the European Southern Observatory in Chile.

The survey will cost \$1.5 million. It is being funded by the Alfred P. Sloan Foundation, the National Geographic Society (the sponsor of the first survey), the National Science Foundation, Eastman Kodak, NASA and Caltech. Once the project is completed, Caltech will make copies of survey photos available at cost to other institutions, either as glass plates or as film transparencies.

—Margaret Marynowski

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