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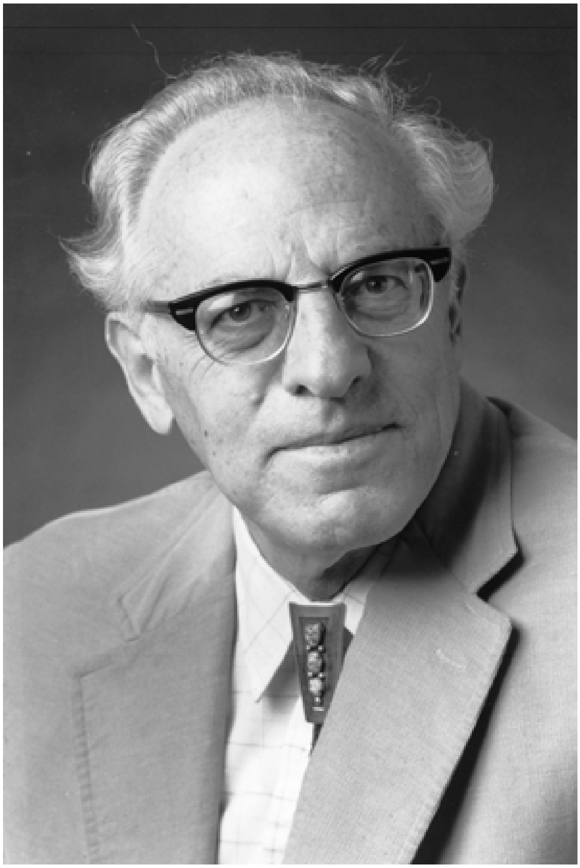
FREDERICK REINES
1918—1998

A Biographical Memoir by
WILLIAM KROPP, JONAS SCHULTZ,
AND HENRY SOBEL

Biographical Memoir



F. Reines

FREDERICK REINES

March 16, 1918–August 26, 1998

BY WILLIAM KROPP, JONAS SCHULTZ,
AND HENRY SOBEL

FREDERICK REINES WAS A man of imposing physical stature and presence, with an even more imposing appetite for physics and a passion for discovery. His energy, drive, and far-reaching vision carried him to the very heights of discovery but never quite satisfied his yearning for more. His philosophy could be described by a line from Robert Browning he sometimes quoted: "Ah, but a man's reach should exceed his grasp/Or what's a heaven for?"[1] His scientific longing and reach often led him to envision and plan experiments of the most challenging nature on what seemed to be an exceptionally broad, expansive scale. Despite the financial vicissitudes that would often, to his consternation, constrain the size of the realized project, his sustained effort and far-sightedness would invariably pay off with genuinely remarkable results. John Wheeler described him as "talented in both theory and experiment, a bear of a man given to thinking big about nearly impossible problems as he paced up and down in his oversized shoes."[2]

Reines's achievements brought him many distinguished awards, the highest of which was the 1995 Nobel Prize in Physics, which he shared with Martin Perl, and which recognized Reines's experimental discovery of the neutrino some 40 years earlier. Although Reines's research interests and accomplishments spanned a wide range, including cosmic-ray physics and the investigation of the fundamental conservation laws of nature, it is his career-long pursuit of neutrino physics, and the uncovering of the basic properties of this elusive particle, for which he is best known and with which he is most closely identified. Among his other awards were the J. Robert Oppenheimer Memorial Prize (1981), the National Medal of Science (1985), the Bruno Rossi Prize (1989), the Michelson-Morley Award (1990), the W. K. H. Panofsky Prize (1992), the Franklin Medal (1992), and a host of distinguished lectureships. He was elected a member of the National Academy of Sciences in 1980 and a foreign member of the Russian Academy of Sciences in 1994.

Fred Reines was born in Paterson, New Jersey, on March 16, 1918. He completed a bachelor of science degree in mechanical engineering at Stevens Institute of Technology in 1939, and a master's degree in mathematical physics at the same institution two years later. He went on to receive his Ph.D. in physics at New York University in 1944 with a theoretical dissertation on nuclear fission. His thesis topic was auspicious and led to his recruitment as a staff physicist, and later group leader, in the Theoretical Division of Los Alamos Scientific Laboratory to work on the Manhattan Project. Following World War II he remained on the staff at Los Alamos and served as director of the Operation Greenhouse experiments on Eniwetok Atoll, engaged in experiments on shock waves and spontaneous fission, and several years later began research on solar and cosmic gamma rays.

It was during a sabbatical from his laboratory duties at Los Alamos that Reines conceived the goal of trying to detect the neutrino. Together with his laboratory colleague Clyde L. Cowan Jr., Reines embarked on a series of experiments, first at a nuclear reactor in Hanford, Washington, and later at one of the new Savannah River Plant reactors in South Carolina, which ultimately led, in 1956, to the first detection of the neutrino, a feat considered previously as virtually impossible. Reines continued to perform neutrino experiments at the Savannah River Plant for more than 30 years following the initial neutrino detection, elucidating properties of the neutrino and shedding light on the weak interactions that contributed greatly to contemporaneous theoretical developments.

Seeking to pursue fundamental physics free of the requirements of work at a mission-oriented national laboratory, Reines left Los Alamos in 1959 to become professor and head of the Department of Physics at Case Institute of Technology. It was there that he formed the Neutrino Group, which became world renowned for its pursuit of neutrinos at reactors and in underground mines. In 1963 Reines formed a collaboration with a group from the University of Witwatersrand in Johannesburg, South Africa, to perform an experiment searching for neutrino interactions at a depth of more than 2 miles in a gold mine in South Africa. This led to the first detection of interactions of muon neutrinos created in the atmosphere, a result also reported about the same time by a group working in the Kolar Gold Fields in India. This collaboration continued as the Case-Witwatersrand-Irvine (CWI) collaboration when Reines left Case Institute in 1966 to become the founding dean of physical sciences at the new campus of the University of California, Irvine. Moving almost his entire Neutrino Group to southern California, Reines lost no time or momentum in pursuing his experimental goals. Among the hallmark studies that emerged in succeeding years was the first detection of the scattering of antineutrinos on electrons and the detection of weak neutral current interactions of antineutrinos on deuterons. These experiments provided vital and timely information on the parameters of the electroweak theory of Sheldon Glashow, Abdus Salam, and Steven Weinberg.

With the development in the 1970s of the so-called Grand Unified Theories of the elementary particles, which predicted proton instability with possibly detectable lifetimes, attention of particle physicists turned to tests of baryon conservation. Long before these developments Reines had maintained a strong interest in the question of baryon conservation as a fundamental principle to be tested. In 1979 together with physicists from the University of Michigan and Brookhaven National Laboratory, Reines led the formation of the IMB (Irvine-Michigan-Brookhaven) collaboration to excavate a giant underground cavity in a mine in Painesville, Ohio, to function as a water Cerenkov detector in a search for proton decay. Reines served as one of the spokespersons for this experiment, which operated for almost a decade, and in searching unsuccessfully for proton decay, managed to set stringent lower limits to the lifetime that ruled out many of the new theoretical models. The experiment also demonstrated an anomalous composition of atmospherically produced neutrinos—a deficit of muon-type neutrinos—which led to the first reported indication of neutrino oscillations. This phenomenon, in which neutrinos change from one type to another, was subsequently confirmed by other experiments (including some in which his Neutrino Group participated) and is currently the subject of intense investigation.

Another major success of the IMB project was the detection on February 23, 1987, of a burst of neutrinos from Supernova 1987A in the Large Magellanic Cloud, approximately 168,000 light years distant. Together with the coincident detection of a neutrino burst from this supernova by the Kamiokande experiment in a mine in Japan, this observation yielded the first direct experimental verification and quantitative information on the role of neutrinos in stellar collapse. The event was hailed by many physicists and astronomers as the "birth of neutrino astronomy." For Reines who had long foreseen the possibility of such supernova neutrino detection, and who had pioneered the development of large water Cerenkov detectors in the late 1950s, as well as other modern-day particle detection devices and techniques, it was a dream come true and the culmination of an extraordinary career.

CHILDHOOD AND EDUCATION

The youngest of four children, Reines was born to Jewish parents who had come from the same small town in Russia to the United States and met and married in New York City.[3] A Russian granduncle, Rabbi Isaac Jacob Reines (1839-1915), was well known as the founder of the Mizrachi Religious Zionist movement; a street in Tel Aviv is named in his honor. Reines's parents, Israel and Gussie (Cohen), provided a warm upbringing, which included religious observance and instruction. Although Reines enjoyed some of the cultural aspects of the religion, participation in organized religion did not seem to play a significant role in his later life.

Reines recalled his father as very skilled with his hands, a somewhat "frustrated machinist." He had worked as a weaver prior to World War I and opened a silk mill after the war, importing silk from Japan. He settled in Hillburn, New York, where he ran a general store, and where Reines spent his early childhood. Years later Reines fondly remembered life in a small American town, marked by sleigh riding in winter and July 4th celebrations with fireworks and strains of John Philip Sousa marches and patriotic songs emanating from a bandstand in the town pavilion. He enjoyed music and participation in school vocal groups, and singing was to become a lifelong passion.

His earliest memory of an interest in science was of an incident in class in religious school when, bored with the lesson, he looked out the window through the curled fingers of his hand simulating a telescope. He noticed what appeared to be a pattern of fringes, an effect he considered peculiar and pondered. His fascination with vision and light persisted. Later, as a student at Stevens Institute he wrote his master's thesis on "A Critical Review of Optical Diffraction Theory." And considerably later he pursued a research project aimed at designing a device that would interface with the neural system to enable the blind to see.

Reines was influenced in his early education by his older siblings, who kept the home provided with books and educational materials. Their studies led them to professional careers; brothers David and William became lawyers and sister Paula became a medical doctor. By the time Reines was in high school his family had relocated to North Bergen, New Jersey, where he was a student at Union Hill High School. He initially did not do well in his science studies, and was attracted more to literary activities. That changed when he succeeded in winning a science prize; his science teacher strongly encouraged him and gave him a key to the laboratory to have free access and work whenever he wanted. He also expressed his interest in science as a member of the Boy Scouts, where he built crystal radios "from scratch." He took an especially serious interest in the Scouts, rising through the ranks to eagle scout and leadership roles. At the same time, he continued his literary interests, serving as editor in chief of the high school yearbook, where his response to the question about his principal ambition in life revealed how far he had come in the direction of science: "To be a physicist extraordinaire."

Reines was accepted for undergraduate studies at MIT, planning to pursue science or engineering, and was advised that he was in line to receive a scholarship. Nevertheless, he detoured after a chance meeting on a bus with an admissions officer of Stevens Institute of Technology. The latter so impressed him with his knowledge and enthusiasm that Reines enrolled in Stevens instead. He majored in engineering, participated in drama and dance groups, and found his true passion outside of physics singing with the chorus. There he quickly moved on to singing solo roles in major choral works, including Handel's *Messiah*, and with the encouragement of the chorus leader undertook singing lessons with a voice coach at the Metropolitan Opera. He could not afford to pay for lessons, but his promise as a singer was sufficiently great that the lessons were provided to him without charge. Indeed, he briefly considered pursuing a professional singing career, but fortunately for physics decided to continue in science.

For doctoral work Reines went to New York University, where he was initially introduced to experimental cosmic-ray physics working under Serge A. Korff. However, for his Ph.D. thesis he turned to theory and, working under Richard D. Present, completed a dissertation on "The Liquid Drop Model for Nuclear Fission." This work extended and generalized the original fission calculations of Niels Bohr and John Wheeler, and succeeded in predicting an activation energy for the fission of uranium isotopes in agreement with experiment. While the work, which began in 1940, was completed in 1943, it was "voluntarily withheld from publication" until the end of World War II, and published as a letter to *Physical Review* together with Present and Julian K. Knipp in 1946.[4]

During his student years, on August 30, 1940, Reines married Sylvia Samuels. Theirs was an extremely close and devoted marriage. Sylvia exerted an important influence; she was protective of Fred and always provided strong emotional and moral support. She also provided a stabilizing influence, helping to keep in balance Fred's enormous enthusiasm and creative energies. Sylvia survived Fred and passed away in 2006.

LOS ALAMOS YEARS

Given the times and Reines's research experience, it was inevitable that he would be recruited to join the Manhattan Project at the Los Alamos Scientific Laboratory (LASL) in New Mexico. In 1944 he became a member of the Theoretical Division headed by Hans Bethe, and was assigned to a group (T-4) working under Richard Feynman. Other members of Feynman's group were Julius Ashkin, Richard Ehrlich, and Theodore Welton. A principal focus of T-4 was the theory of diffusion and its important implications for calculation of the critical mass.

Not long after arriving, Reines was himself elevated to group leader in the Theoretical Division. About one year after the end of the war he seriously considered the offer of an academic appointment at the University of Iowa but ultimately decided to remain at Los Alamos. He became involved in various studies and theoretical analyses of the effects of nuclear weapons, becoming in particular an authority on blast effects. One such analysis was an exploration with John von Neumann of the formation of the "Mach stem," an enhancement of the shock wave caused by the joining of the incident blast wave from a bomb exploded in the air with the wave reflected from the surface.[5] He participated in many of the postwar nuclear bomb tests, analyzing and interpreting results and writing substantial segments of director's reports for operations. Tests in which he participated included Crossroads (Bikini, 1946), Sandstone (Eniwetok, 1948), Ranger and Buster-Jangle (Nevada Test Site, 1951). Reines served as Program 1 director for Operation Greenhouse, which took place at Eniwetok in the Marshall Islands in April and May of 1951; his role involved oversight of the weapons and phenomenology part of the operation. Among the four detonations performed in Operation Greenhouse, two were directly concerned with testing principles associated with thermonuclear fusion. One ("George") was the first true test of the use of a fission bomb to ignite fusion of a small amount of deuterium and tritium; the other ("Item") tested the concept of boosting the yield of a fission bomb by the injection of the 14 MeV neutrons from D-T fusion into the fission core. Reines's central involvement in Operation Greenhouse probably contributed to the scientific relationship of mutual respect that he maintained for years with Edward Teller, the principal force behind the thermonuclear weapons development.

Reines was also very much concerned with the radioactive pollution and contamination caused by nuclear weapons. His expertise with respect to blast effects and his analyses of the radioactive debris caused by explosions in the air played a role in formation of the consensus that led to the eventual decision to halt aboveground testing and to begin the use of underground tests.[6] He continued to be involved in important defense discussions, including his participation in the 1958 summer study Project 137, which consisted of wide-ranging discussions of defense issues led by John Wheeler.

The years in Los Alamos were happy ones for Reines and his wife, Sylvia. They enjoyed the social environment and camaraderie with the extraordinary group of scientists and their families assembled there. He took up singing with the town chorus and performed in productions of Gilbert and Sullivan operettas. He also performed in theater productions of the Los Alamos Little Theater, especially enjoying the lead role in *Inherit the Wind.* Sylvia also was involved in the community and was an early member and president of Hadassah, the Jewish women's service organization. Their two children were born in Los Alamos: Robert in 1945 and Alisa in 1948. Robert, who lives in Ojo Sarco, New Mexico, pioneered the development of energy-independent housing, and went on to obtain a Ph.D. in engineering. Alisa (Cowden) obtained an M.F.A. degree and works as an illustrator; she resides in Trumansburg, New York. Reines's children ultimately presented him and Sylvia with six grandchildren, in whom they took great pride.

DISCOVERY OF THE NEUTRINO

Following intensive involvement in bomb testing, in 1951 Reines decided to ask for a sabbatical to pursue research on more fundamental physics. His goal, as always, was to select a difficult and challenging problem. The request having been granted by Theoretical Division leader J. Carson Mark, Reines "moved to a stark empty office, staring at a blank pad for several months, searching for a meaningful question worthy of a life's work."[7]

He could not have chosen a more imposing problem than the one he ultimately settled on: the direct detection of the neutrino. The neutrino had been postulated by Wolfgang Pauli in 1930 in a famous letter to a congress assembled in Tubingen, which began, "Dear Radioactive Ladies and Gentlemen," in order to solve the problems of the apparent violation of energy conservation in nuclear beta decay and "wrong" statistics of nuclei.[8] To accommodate existing measurements, Pauli's particle had to be electrically neutral and nearly massless. By 1934 Enrico Fermi (who christened the new particle "neutrino") incorporated the spin-1/2, massless (or very tiny mass) object into his beautiful and simple theory of beta decay. A consequence of this theory, as immediately pointed out by Hans Bethe and Rudolph Peierls,[9] was that the inverse process, in which a neutrino strikes a nucleus and creates an electron or positron, must have an extremely small cross-section. Their conclusion was that "it is . . . absolutely impossible to observe processes of this kind with neutrinos created in nuclear transformations," and that even for cosmic-ray energies the process could probably not be observed. Their final verdict was that "there is no practically possible way of observing the neutrino." Pauli acknowledged the problem this way: "I have done a terrible thing. I have postulated a particle that cannot be detected." There the matter stood until Reines set his sights on detecting the neutrino. For him the situation was intellectually and scientifically intolerable. He was bent on converting the neutrino, as he later phrased it, from a "poltergeist to a particle."

Reines initially decided that the best, most intense source of neutrinos would be a fission bomb. Indeed, he had been looking for a peacetime application of the bomb that could benefit basic research. He sought out confirmation from Enrico Fermi, who was at Los Alamos at the time. Fermi concurred but was not able to help with suggestions for design of a detector. Disappointed, Reines put the neutrino project on hold until he had a conversation with Los Alamos colleague Clyde Cowan, while the two were grounded in a Kansas City airport waiting for a plane to be repaired. They decided to team up on a project, and Reines convinced Cowan to work together on the neutrino detection. The fortuitous interaction led to a most extraordinary collaboration, a true symbiotic joining of minds, abilities, and temperaments. Reines often referred to his teaming with Cowan as one of the best and luckiest decisions of his career.

With the blessings of Los Alamos director Norris Bradbury, they fashioned an ingenious design consisting of a nuclear explosive on a 30 meter tower, and a detector under backfill suspended in a vertical vacuum tank 40 meters away. Immediately after the explosion, the detector would drop in free fall for a few seconds to protect it from the resulting shock wave, and proceed to collect data from the fission fragment neutrinos. Construction of the detector and the digging of the free fall shaft were underway when in 1952,

J. M. B. Kellogg, a colleague at Los Alamos, urged Reines and Cowan to “review once more” the use of a fission reactor.[10] Reactors allowed for multiple and longer duration experiments, a failure of the bomb scheme. They were, however, less intense neutrino sources and backgrounds were thus a more severe problem.

The ultimate success of the neutrino search stemmed from the inspired idea of Reines and Cowan to reduce the background by using a delayed coincidence between the pulse from the annihilation of the positron emitted in the inverse beta reaction and that from the emitted neutron, which would wander for several microseconds before being captured, yielding gamma rays. With this scheme it became possible to forego a nuclear explosion and to use instead a reactor as the neutrino source.

The detector designed for the first reactor experiment was considered extremely bold for the times: 300 liters of newly discovered organic liquid scintillator (no one had used more than about 30 liters previously), surrounded by 90 2-inch-diameter photomultiplier tubes. One of the first uses of the detector had nothing to do with neutrinos; by inserting a cylindrical steel cylinder inside an annular region filled with liquid scintillator, it became possible to measure the total body radioactivity emitted by live subjects doubled up within the inner cylinder. In this way Reines, Cowan, and a few Los Alamos coworkers determined the radioactivity of several humans and one canine subject, and invented a new biophysical technique.

However audacious the detector design may have impressed people, it became Reines’s hallmark to “think big” but generally not much bigger than demanded by the unimaginably difficult projects he contemplated. When the new experimental design was formulated, Reines and Cowan in a letter duly informed Fermi of their new idea. Fermi once again approved of the plan, and with characteristic perspicacity remarked that the new plan had the advantage that the experiment could be "repeated any number of times."

The first attempt used a Hanford Engineering Works reactor in Hanford, Washington, and by the summer of 1953 Reines and Cowan were able to report in *Physical Review* the probable detection of a neutrino signal. At that point they learned from John Wheeler about new and more powerful heavy-water-moderated reactors at the Savannah River Plant in South Carolina. Running the reactor for 100 days spaced out over about one year, they were able to obtain the definitive results in 1956, proving that the neutrino was no poltergeist. A telegram to Pauli informing him of the results elicited a night-letter response thanking them for the message and remarking, "Everything comes to him who knows how to wait." Unfortunately, the letter never arrived.[11] It would have been particularly wise and prescient advice for Reines, who had to wait four decades for the discovery to be recognized by a Nobel committee. By that time Cowan had died.

CASE INSTITUTE YEARS

Reines and Cowan continued their efforts at the Savannah River Plant with an improved experiment, using more photomultiplier tubes and a larger detector situated closer to the reactor core. This enabled them to obtain a better measurement of the neutrino cross-section and to report a result consistent with the revised theory of beta decay required by the newly discovered violation of parity in the weak interactions. In 1957 Cowan left Los Alamos for a teaching position at George Washington University (and shortly thereafter moved to Catholic University), bringing their collaboration to an end. Reines left two years later to become head of the Department of Physics at Case Institute of Technology in Cleveland, Ohio. There he formed his Neutrino Group and drew to himself a circle of graduate students and fellow faculty, including Marshall F. Crouch, Thomas L. Jenkins, and Robert M. Woods Jr. and an extraordinarily gifted engineer August A. ("Gus") Hruschka, who became a close and highly valued friend. Reines also brought Glenn M. Frye Jr. from LASL to Case; the two had started a collaboration at the laboratory searching for solar and cosmic gamma rays with balloon flights and in particular looking for gamma-ray point sources. Reines's arrival at Case initiated a burst of creative activity, leading to a large number of Ph.D. theses guided by him and his close faculty colleagues.

Reines continued his measurement of neutrino properties at the Savannah River Plant, and initiated a search for an underground laboratory to proceed with investigations of conservation laws and a quest for "natural" neutrinos: from the Sun, cosmic rays, and the cosmos. The nearby Fairport Harbor Mine of the Morton Salt Company appeared ideal; it was more than 600 meters deep, about 20 times deeper than an underground room he had used at Los Alamos. On a long weekend expedition with some rudimentary electronics, a scintillation detector approximately 1 meter square, and several graduate students, Reines measured both the low residual cosmic-ray intensity and the extremely low levels of radioactivity of the salt. He was satisfied that he had found a new experimental home. With a visit to Morton Salt headquarters in Chicago, he cultivated a working relationship with the owners of the company, an association that endured into the 1990s.

At the Fairport Mine, Reines and his group created a laboratory and initiated a multifaceted series of studies searching for solar neutrinos, conservation law violations, and double beta decay. The nature of cosmic rays underground was also probed. New detection techniques were developed involving giant (for those days) scintillation and (normal- and heavy-water) Cerenkov detectors, and scintillation and magnetic spectrometers. The solar neutrino searches used both inverse beta decay and the yet-to-be-observed elastic scattering on electrons; these were the first attempts at direct counting of solar neutrinos and set the first experimental limits on the solar neutrino flux from decay of ^{8}B. It was Reines's insight that the unique directional properties of the elastic scattering reaction could tag neutrinos as coming from the Sun.

In 1963 Reines became aware of a University of Bombay Ph.D. thesis by P. V. Ramana Murthy, which convinced him that the flux of muons was sufficiently attenuated at depths attainable in the mines of the Kolar Gold Fields in southern India to make the detection of atmospheric neutrinos feasible. Within weeks he and Hruschka were in India, meeting with physicists from the Tata Institute of Fundamental Research and visiting the Kolar mines. Although this approach led nowhere, in short order Reines did find a suitable venue in the East Rand Proprietary Mine near Johannesburg, South Africa, and a collaboration with the group of J. P. F. Sellschop of the University of Witwatersrand in Johannesburg.

In a laboratory that had to be reached by a descent of more than 2 miles vertically and almost 6 miles horizontally—a trip that ranged from one to several hours, depending on conditions—the experimenters installed their apparatus in about one year. It was surely the largest particle detector constructed up to that time, consisting of about 20 tons of liquid scintillator in two parallel walls, separated by 1.8 meters; each wall was 1.9 meters high and 56 meters long. Amused South African miners called the experimenters "goggafangers"—translated literally as "bug catchers"; and Reines was the "makulu bass goggafanger," the "big boss bug catcher." Despite political problems, including charges at the United Nations that the experiment involved secret nuclear weapons tests, and protests among university students objecting to collaboration with South Africa, the experiment was carried out from 1963 to 1971, with a significant upgrade completed in 1967. It succeeded ultimately in detecting neutrinos produced from cosmic-ray interactions in the atmosphere; the first event was detected on February 23, 1965 (an interesting coincidence with the date of Supernova 1987A) and the experiment yielded a total of 35 of the rare events in the first phase and 132 in the second.

While at Case, Reines was able to indulge his passion for singing, performing with the Cleveland Symphony Chorus under the direction of the distinguished music director and conductor George Szell and associate conductor Robert Shaw.

UNIVERSITY OF CALIFORNIA, IRVINE, YEARS

In 1966 Reines arrived on the newly built campus of the University of California, Irvine (UCI), as the first dean of the School of Physical Sciences. Pouring his energies into the new task, he became a vigorous proponent of the school and ferocious seeker of resources. Informed on one occasion that his school had been given "the lion's share" of new funds, he grumbled that "around here, with the lion's share one could starve to death." In addition to his administrative duties, Reines enjoyed teaching and particularly relished giving a course for undergraduate nonscience majors on the wonders of physics he called "Rainbows and Things." Besides his appointment in physics, he also held an appointment as professor in the Department of Radiological Sciences in the UCI Medical School.

Reines brought his Neutrino Group with him to UCI, continued his South African collaboration, and maintained an ambitious program of reactor experiments at the Savannah River Plant. Among these were studies of antineutrino interactions with the deuteron, using a heavy-water target.

As early as 1956 Reines and Cowan had attempted, unsuccessfully, to detect disintegration of the deuteron by reactor antineutrinos; further experiments were pursued with colleagues from Case Institute. By the 1970s such studies acquired added significance since they offered the possibility of detecting weak neutral current interactions predicted by the newly formulated theories of electroweak unification. Weak neutral currents were ultimately confirmed in high-energy neutrino experiments at CERN and Fermilab. In 1979 Reines and the UCI group reported the first detection of deuteron disintegration by weak neutral currents. A previous experiment with Henry Gurr and Henry Sobel, reported in 1976, had been the first to detect the elastic scattering of antineutrinos by electrons, another process induced by weak neutral currents. The deuteron disintegration and electron scattering detections were both very difficult and extremely challenging experiments, but because of the relative simplicity of their theoretical interpretations, they made important contributions to the elucidation of the electroweak theory. Additionally, the deuteron experiments were among the first to probe the possibility of neutrino oscillations—now a confirmed phenomenon.

Pursuing these experiments at the Atomic Energy Commission's high security and high priority Savannah River Plant occasionally raised delicate problems, since the reactor served as a key component of the nation's nuclear weapons program. An essential test for understanding the background in the neutrino experiments required comparing the count rates with "reactor on" and "reactor off." Opportunities for the latter occurred naturally at times when the reactor was turned off for programmatic reasons. But such was Reines's standing with the AEC that on one occasion, with students and coworkers looking on in astonishment, he succeeded in getting the reactor operators to turn off the nation's tritium and plutonium production for the sake of his pursuit of the transient neutrino.

At UCI, Reines also intensified his longstanding interest in studying the fundamental conservation laws and symmetry principles of physics. An experiment previously performed at Case with his graduate student Michael Moe had looked for the emitted radiation that would follow any disappearance of a K-shell electron in a sodium iodide crystal, thus signaling a violation of charge conservation. The experiment set important new limits on charge nonconservation and on the lifetime of the electron. A later reanalysis of the experiment with Sobel interpreted the results in terms of limits on the violation of the Pauli Exclusion Principle, a cornerstone of physics that intrigued Reines and caused him sleepless nights seeking ways to perform direct experimental tests.

Baryon conservation, however, was his principal obsession among the basic conservation laws. The first experiment explicitly designed to test the principle by looking for nucleon decay was performed by Reines together with Cowan and Maurice Goldhaber in 1954, using the large scintillation detector developed for the neutrino search. A long series of similar studies continued at Los Alamos and at Case with several different sets of coworkers, and with increasingly sensitive detectors, obtaining successively better limits on nucleon instability. His dedication was such that over 20 years he increased the sensitivity of the search by eight orders of magnitude. While these studies were an expression of Reines's core belief in the importance of testing experimentally the most fundamental principles of the subject, they were of primarily esoteric interest until the early 1970s.

Following the successful unification of electromagnetism and weak interactions, attention of theorists turned to the possibility of further unification with the strong interactions, resulting in the Grand Unified Theories with predictions of proton decay at rates that seemed experimentally accessible with a sufficiently large detector. Several experimental groups entered the race, including the Irvine-Michigan-Brookhaven collaboration, with Reines of UCI and Jack Vander Velde of the University of Michigan as cospokesmen. Goldhaber, a pioneer in proton decay studies, was the lone representative from Brookhaven, and ultimately several other universities joined the group. A cavity measuring approximately $17 \times 18 \times 23\ m^3$ was carved out of the salt at a depth of about 2000 feet below the surface of the Morton mine Reines had previously used as a base for experiments. The cavity was lined with high-density polyethylene and filled with 8000 metric tons of highly purified water, viewed by 2048 5-inch-diameter (later replaced by 8-inch-diameter) photomultiplier tubes. It was the culmination of Reines's progression to increasingly larger detectors. Operating for about 10 years, the IMB detector set the (then) best limits on nucleon decay, recorded many atmospheric neutrino interactions, and ultimately saw the historic neutrino burst from Supernova 1987A. One of Reines's earlier detectors had been adorned with a sign hopefully proclaiming it to be a supernova early warning system. The goal had finally been achieved.

Although Reines had stepped down from his position as UCI's dean of physical sciences in 1974, his administrative services to the University of California continued for 20 more years. Starting in 1975 he was a member of the Scientific Advisory Committee (SAC), which advised the university president and the Board of Regents on a wide range of matters concerning the weapons laboratories managed by the university at Los Alamos and Livermore. Reines's weapons lab experience made him a valuable member of the committee, which he chaired for three years (1986-1988), shortly after "academic" had been added to "scientific" in the committee's title and responsibilities. These were somewhat troublesome years for the SAAC, while questions were raised broadly about the appropriateness of the relationship between the University of California and the laboratories, and about the laboratories' weapons strategies vis-à-vis a comprehensive test ban.

In 1988 UCI elevated Reines to Distinguished Professor of Physics Emeritus. To celebrate his 70th birthday that year the university hosted a "Reinesfest" Symposium, featuring several distinguished speakers reviewing the highlights of his career. The event was followed by the publication of a collection of his important papers, a testimony to the distinctive role he played in the physics of his time.[12]

REINES AS MENTOR

During his years at Case and at UCI, Reines guided a number of students to the Ph.D.,[13] and played a significant role in mentoring and inspiring the students of his colleagues. In addition, Reines took pride in nurturing and supporting the efforts of postdoctoral researchers and faculty colleagues working on projects in which he was not a coinvestigator. His weekly Neutrino Group meetings gave these researchers the opportunity to discuss their ideas and work progress and gain from critical analysis and advice of the assembly. Colleagues who benefitted from his serious and concerned patronage in this manner included Michael Moe, in his groundbreaking detection of double beta decay; Riley Newman, whose laboratory gravity experiments and other experimental pursuits earned Reines's thorough admiration; and Herbert Chen, who started as a postdoctoral theorist in the group and went on to lead his own neutrino experiments and to conceive of and initiate the Sudbury Neutrino Observatory project.

Fred Reines's influence and impact on physics were multifold. His legacy is embodied not only in the discoveries he made and the innovations he authored but also in the example he set of dedicated, unyielding pursuit of knowledge and in the inspiration of those who knew and worked with him.

NOTES

1. The line is from Browning's poem "Andrea del Sarto." Reines had a deep knowledge and great love of poetry, which he would write as well as quote.
2. J. A. Wheeler and Kenneth Ford. *Geons, Black Holes & Quantum Foam: A Life in Physics,* p. 281. New York: W.W. Norton, 1998.
3. Parts of this section lean heavily on Fred Reines's own words, as recalled by his colleagues and as recorded in the autobiographical comments provided to the Nobel Foundation (http://nobelprize.org/nobel_prizes/physics/laureates/1995/reines-autobio.html).
4. R. D. Present, F. Reines, and J. K. Knipp. The liquid drop model for nuclear fission. *Phys. Rev.* 70(1946):557-558.
5. F. Reines and J. von Neumann. The Mach effect and height of burst. In *Blast Wave,* vol. 7, ed. H. Bethe, pp. 309-347. Los Alamos Scientific Laboratory Technical Series, 1947.
6. His knowledge of blast effects also enabled Reines to recalculate the energy release of the Hiroshima atomic bomb. In 1953 Reines mentioned to Luis Alvarez that the damage done at Hiroshima was not consistent with the figure of 20 kilotons of TNT that had been announced immediately following the event. Alvarez gave Reines records from his files with data he had personally collected on the plane following the Enola Gay. Reines used the data to calculate an energy release of 12.5 ± 1 kilotons, close to the currently accepted value of about 14 kilotons (L. W. Alvarez. *Alvarez: Adventures of a Physicist,* p. 143. New York: Basic books, 1987).
7. F. Reines. The neutrino: From poltergeist to particle. Nobel lecture. *Rev. Mod. Phys.* 68(1996):317-327.
8. See, for example, A. Pais, *Inward Bound: Of Matter and Forces in the Physical World,* p. 315. Oxford: Clarendon Press, 1986.

9. Although Fermi's original detailed paper (E. Fermi, Tentativo di una teoria dei raggi ß. *Nuovo Cimento* 11(1934):1-19) addressed the issue of how to determine the mass of the neutrino, it did not discuss the difficulty of detecting it. That remained for Bethe and Peierls (The "neutrino." *Nature* 133[1934]:532.)
10. The Reines-Cowan experiments—detecting the poltergeist. *Los Alamos Science* 25(1997):4-27. Lawrence Cranberg also recalls suggesting the use of a reactor to Reines and Cowan (Lawrence Cranberg, private communication).
11. Reines learned about the letter years later (in 1986) from C. P. Enz, a student and biographer of Pauli.
12. *Neutrinos and Other Matters: Selected Works of Frederick Reines,* eds. W. Kropp, M. Moe, L. Price, J. Schultz, and H. Sobel. Singapore: World Scientific, 1991.
13. In chronological order, Reines's Ph.D. students at Case Institute: Charles C. Giamati (1962), William R. Kropp (1964), Frank A. Nezrick (1965), Michael K. Moe (1965), Henry S. Gurr (1966), and Jack H. Munsee (1968). At UCI: James W. Brooks Jr. (1972), Dennis D. Lowenthal (1976), Elaine L. Pasierb (1979), and Todd J. Haines (1986).

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