Stuart Jay Freedman

1944–2012

BIOGRAPHICAL *Memoirs*

A Biographical Memoir by
R. G. Hamish Robertson

NATIONAL ACADEMY OF SCIENCES

STUART JAY **FREEDMAN**

January 13, 1944–November 10, 2012

Elected to the NAS, 2001

By R. G. Hamish Robertson

Stuart J. Freedman was an experimental physicist with a broad sweep of talents and interests that centered on nuclear physics but also spanned particle physics, quantum mechanics, astrophysics, and cosmology. As a graduate student at the University of California, Berkeley, he carried out a crucial test of the Einstein-Podolsky-Rosen (EPR) argument that quantum mechanics was an incomplete theory; Stuart showed that EPR's postulated local hidden variables did not explain experimental data, whereas quantum mechanics did. Stuart was an early and continuous leader in the search for neutrino oscillations, and in the KamLAND project he determined which of several possible solutions the correct one was. He also was noted for several instances in which an incorrect result with major implications was neutralized. Perhaps the most famous case involved the 17-keV neutrino.

Stuart was born in Hollywood, CA—the son of David Freedman, an architect, and Anne (Sklar) Freedman—and attended schools in Beverlywood. By all accounts he was a strong student and a "normal" teenager, with a penchant for ruffling establishment feathers whenever possible. His occasional minor run-ins with the law and hilarious interactions with bureaucracies became the stuff of good stories later in life. He also was athletic, swimming competitively and playing football. Stuart entered UC, Berkeley, in 1961, graduated with a B.S. in engineering physics in 1965, and decided to stay on for graduate work in physics. He and Joyce Schechter, who had known each other since high school, married on December 16, 1968.

After working in theoretical particle physics under Charles Zemach for about a year, Stuart sought a more satisfying experience in experimental physics and approached Eugene Commins, who, together with student Carl Kocher, had some years before developed atom-scale techniques for producing what are now described as "entangled" photon pairs. Charles Townes, who in 1967 had just arrived at Berkeley, had been asked by his incoming postdoctoral fellow, John Clauser, about the possibility of making an experimental test of the hidden-variable hypothesis of EPR. Townes and Commins conferred and it was soon agreed that such a test could be made using entangled photons, that Stuart would be advised by Commins, and that Townes and Commins would split the cost.

Einstein, as is well known, found the probabilistic aspects of quantum mechanics troubling; he grumbled that "God does not play dice." A way to preserve the deterministic view was to posit that certain hidden variables existed, and it was their action that determined the outcome of experiments that otherwise seemed "nonlocal," or disturbingly dependent on other outcomes at remote locations. Such a proposal, however, seemed for a long time to be untestable until 1964, when John Bell proved that its predictions were indeed different from those of quantum mechanics.

The entangled photons produced in a cascade of neutral calcium atoms by Kocher and Commins were well suited for a test of Bell's inequality—the mathematical statement of the difference between results from quantum mechanics and from a putative local hidden-variable theory. Two highly efficient polarizers and photon detectors positioned on either side of the calcium vapor source could be set to any desired angle. Quantum mechanics and hidden-variable predictions agreed when the polarizers were aligned (the coincidence detection rate was minimized) and when they were crossed (the coincidence rate was minimized, at nearly zero). The two theories also agreed about the coincidence rate when the polarizers were set at 45 degrees to each other. However, for smaller misalignments, quantum mechanics predicted a larger coincidence rate than did the hidden-variable theory.

These results derived from the relationship of the polarizations of the two entangled photons, which remained a single quantum-mechanical object: the coincidence rate changed quadratically with the relative misalignment of the two polarizers. In hidden-variable theories, the locality assumption at each detection point made this dependence additive and linear. It was necessary to assume that the efficiency for detecting a photon was the same, whether it had passed through a polarizer or not—an assumption that was subsequently tested by others and found to be valid. The 1972 experiment clearly showed the explicit violation of Bell's inequality, as predicted by quantum mechanics and in conflict with the EPR recourse to hidden variables. A picture of Stuart Freedman with the apparatus is shown in Figure 1.

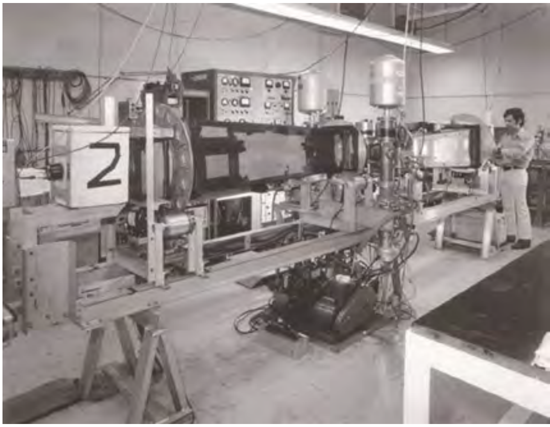


Figure 1. Stuart stands with the aparatus to test Bell's inequality.

In bringing this experiment to its successful conclusion, both Freedman and Clauser played vital roles. The idea to do the experiment and the initiative to do it in the environment of the experienced Berkeley group, came from Clauser. The actual experimental work was, for the most part, Freedman's. The Freedman-Clauser experiment was a classic, the first in a long series of important tests of such fundamental concepts as locality and realism in the framework of quantum mechanics. Moreover, its significance appears to have grown with time. Asked why he did not continue his highly successful expedition into the foundations of quantum mechanics, Stuart responded that he found the field to have attracted more than its share of people at the fringes of science, and he did not find this aspect enjoyable.

Completing his dissertation work at Berkeley in 1972, Stuart took an instructor position at Princeton University, where he worked with Frank Calaprice. Calaprice had developed methods for studying the weak interaction, using polarized ^{19}Ne that had been produced in the Princeton cyclotron, which enabled researchers to address interesting questions such as whether so-called "second-class" currents existed in the weak interaction or whether time-reversal symmetry was violated. After completing two publications with Calaprice (1975 and 1977), Stuart moved toward more specifically nuclear problems.

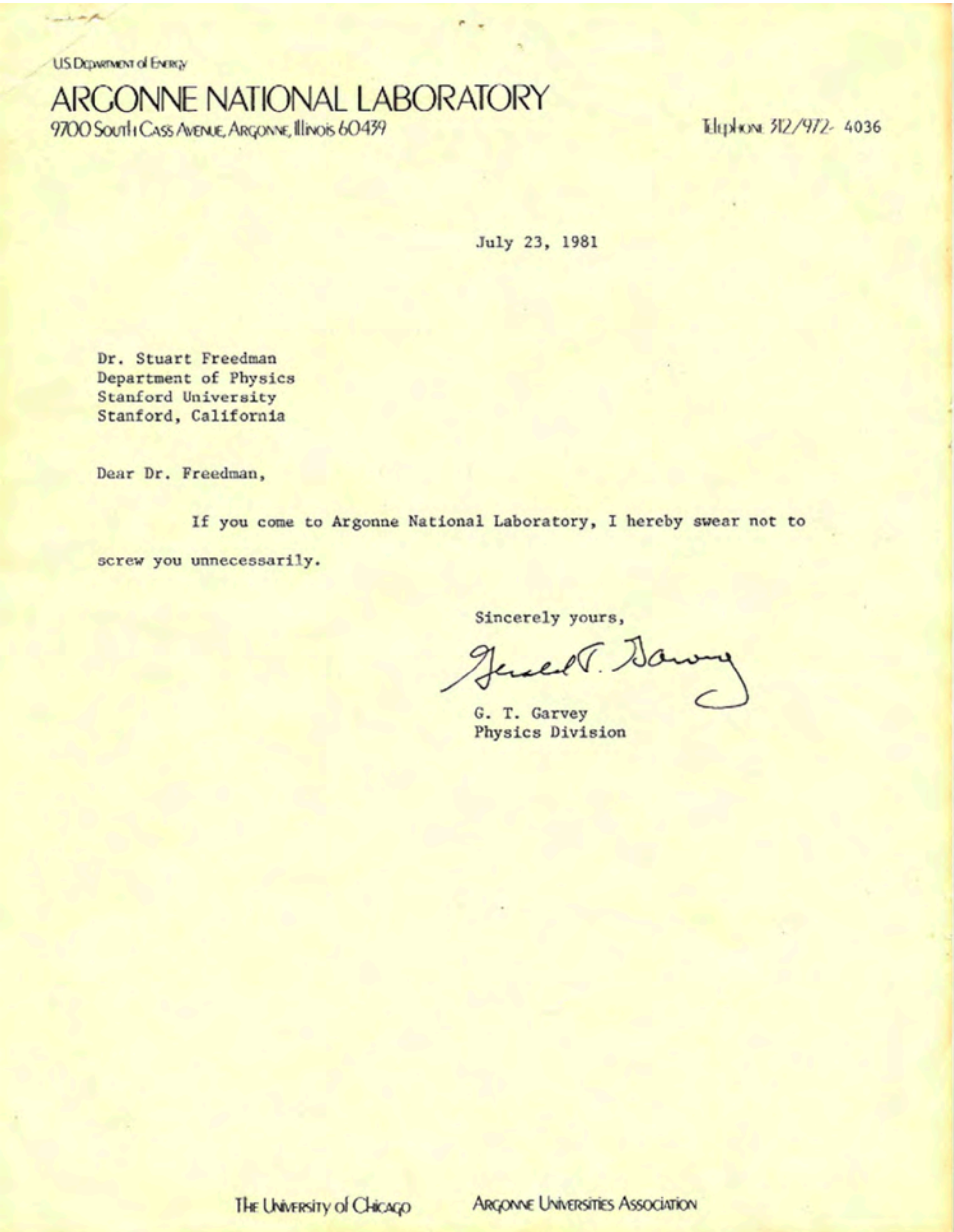
The presence of Gerald Garvey at Princeton influenced not only Stuart but also a large number of other young physicists at a similar stage in their careers. The year 1975–1976 alone brought Eric Adelberger, Rosemary Baltrusaitis, Thomas Bowles, Robert Cousins, Robert Del Vecchio, Carl Gagliardi, John Greenhalgh, Jerry Lind, Robert McKeown, Anthony Nero, Michael Oothoudt, Hamish Robertson, Ben Svetitsky, Robert Tribble, Frederick Zutavern, and others together in an energetic and merry group. The work on isospin-symmetry violation in nuclei that Stuart led was not particularly memorable, but Stuart emerged as the glue that kept most of this group of physicists together throughout their careers. Steve Girvin was a graduate student at Princeton then as well, and he taught Stuart and others in the group to fly sailplanes, a pastime that Stuart enjoyed for years afterward.

In 1976 Stuart accepted an assistant professorship at Stanford University in order to work with Stanley Hanna's group, and he remained at Stanford until 1982 without receiving tenure. His relationship with Hanna was difficult from the beginning, reflecting their very different views on the level of authority that should appropriately be exerted by senior personnel within a research group.

While at Stanford, Stuart, together with Alan Litke, developed the first experiment—a fractional-charge search (1982)—to run on the new electron-positron storage ring PEP; from this effort, Jim Napolitano earned his Ph.D. under Litke. In 1978 Stuart was awarded an Alfred P. Sloan Foundation Fellowship, his first substantive recognition by the larger physics community. These successes aside, the experience at Stanford was discouraging, but his mentor Gerald T. Garvey told him, "Stick around, and sooner or later someone will make a mistake." Good to his word, Garvey, who had just moved to Argonne National Laboratory, recruited Stuart. But Stuart claimed not to trust Garvey and insisted that his mentor should write him a letter promising his good faith in the matter. The letter is reproduced in its entirety in Figure 2 and illustrates, among other things, the irreverence of both individuals toward the bureaucratic process.

At Argonne, Stuart began to receive anew the resources and encouragement that allowed him to flourish once again in physics. His work on the beta spectrum of ^{8}B (1987) and on the neutron capture cross-section of ^{3}He (1989) is the basis of modern calculations of the shape of the solar high-energy neutrino spectrum. The Sudbury Neutrino Observatory experiment, which later demonstrated that the "solar neutrino problem" was caused by new-neutrino physics, relied on the Napolitano-Freedman-Camp spectrum (confirmed with new data by Stuart's group in 2003) to pin down the allowed regions of parameter space for this phenomenon. The solar neutrino problem was that the measured flux of neutrinos was less than half as large as expected, based on the rate of energy production by the sun; this apparent deficit of neutrinos was shown by SNO to result from electron neutrinos converting to mu and tau neutrinos on their journey from the sun to Earth. Such neutrino "flavor" conversion, a manifestation of quantum-mechanical neutrino oscillations, requires that neutrinos have non-zero mass.

Stuart played a major role in experiment E645—a search for neutrino oscillations—at the Los Alamos National Laboratory's Meson Physics Facility. This was a large and



U.S. Department of Energy
ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue, Argonne, Illinois 60439

Telephone 312/972- 4036

July 23, 1981

Dr. Stuart Freedman
Department of Physics
Stanford University
Stanford, California

Dear Dr. Freedman,

If you come to Argonne National Laboratory, I hereby swear not to screw you unnecessarily.

Sincerely yours,

Gerald T. Garvey

G. T. Garvey
Physics Division

The University of Chicago   Argonne Universities Association

Figure 2. Letter to Stuart from Gerald Garvey. (Courtesy Joyce Freeman.)

complex experiment with a somewhat fractious collaboration. Stuart's group had responsibility for the 670-ton active veto to reject cosmic rays (1983). It consisted of a large annular steel tank, filled with liquid scintillator, and photomultiplier instrumentation. Stuart recounted with wry amusement that they had specified to the manufacturer that the tank "must be helium-leak tested." Yet on delivery, the tank was found to leak like a sieve; in fact, many of the welds were missing entirely. Stuart reminded the company about the requirement, and the response was, "We did test it. It leaked." But the repaired instrument was completed on time, performed flawlessly (1993), and was subsequently incorporated into a successor oscillation experiment, LSND. This was Stuart's first foray into neutrino-oscillation physics, a field to which he would return 10 years later with spectacular impact.

The beta decay of the free neutron provides a great deal of information about the weak interaction and the fundamental symmetries of nature. The direct and unobstructed access to such basic questions was attractive to Stuart, who was instrumental in conducting a series of experiments that set the standard in the field. The research reactor of the Institut Laue-Langevin in Grenoble, France, was the international venue for fundamental neutron physics, and it was there that Stuart formed a close collaboration with Dirk Dubbers. The "Perkeo" detectors they built yielded precise new data on the beta asymmetry of the neutron (the correlation between the neutron spin and the electron momentum directions), which in turn provided the ratio of the strengths of the vector and axial-vector parts of the interaction (1988). The same apparatus was used to determine the neutron lifetime with a novel approach, although precision was limited. The neutron guide hall at the NBS Reactor in Gaithersburg, MD, was another attractive site for this kind of research, and an experiment originally proposed by Thomas Bowles in 1982 to measure the so-called D coefficient in neutron beta decay was carried out there by Stuart and his colleagues. The parameter D is non-zero only if time-reversal symmetry is violated; an upper limit on its size was found (2012). The D-coefficient project began in 1995, after Stuart had moved back to Berkeley.

In 1985, John Simpson and his student Andrew Hime at the University of Guelph in Ontario were exploring a novel method for measuring the mass of the neutrino; they were motivated by a 1981 paper of a Russian group, which reported that the electron neutrino had a mass of 30 eV. To address this question in a way less dependent on systematic uncertainties, Simpson and Hime implanted a silicon detector with tritium from an accelerator and measured the beta spectrum from its decay. The classic method of beta decay relies on a change of shape of the beta spectrum near the "endpoint," where the electron takes all the energy available in the decay. If the neutrino has some rest mass, the electron cannot take that last bit of energy, and the spectrum shows it. They did not find evidence for or against the Russian result but did observe a striking deviation in the shape of the spectrum at an energy 17-keV below the endpoint. A neutrino of such a mass was completely unexpected. Soon laboratories around the world were racing to check this evidence for a 17-keV neutrino weakly admixed with the electron neutrino. To much surprise, supporting evidence was forthcoming from many different isotopes: ^{14}C, ^{35}S, and ^{63}Ni, as well as tritium. Some experiments, however, particularly those using magnetic spectrometers, did not produce evidence for a 17-keV neutrino, although the sensitivity and robustness of those experiments was challenged with some success.

Into this confusing scene came Stuart Freedman, a physicist with a justly earned reputation for his ability to master systematic uncertainties and minimize them. Stuart was aware of the existence at Argonne of a unique electron spectrometer, designed and built by Zbigniew Grabowski, in which the radioactive source was positioned in the high magnetic field of a superconducting solenoid and the silicon detector was in a low-field region. In that arrangement, electrons from the source cannot scatter from the apparatus before entering the detector, an effect that Stuart suspected (correctly, as it transpired) was responsible for the spectrum modification in many cases. Working with a University of Chicago undergraduate student, Justin Mortara, Stuart carried out a measurement of the spectrum of ^{35}S and published the result in 1993. He and Mortara saw no evidence for the spectrum distortion, and they further showed by adding a trace of a different isotope, ^{14}C, that they would have seen it had it been present. Their result was universally accepted as definitive and the question was settled: there was no 17-keV neutrino. Subsequent work by Hime and others disclosed the role of scattering, as Stuart had surmised. The cause of the original Simpson-Hime result, which also was immune to scattering, was probably attributable to theoretical uncertainties.

The year 1989 saw another flurry of excitement in physics when Martin Fleischmann and Stanley Pons, and, contemporaneously, Steven Jones, claimed evidence for cold fusion in the electrolysis of heavy water on palladium electrodes. Fleischmann and Pons reported excess heat production, and Jones reported the production of neutrons, both indicators of fusion reactions. Many researchers attempted to duplicate the results, generally without success. Without setting foot in the lab, Stuart noticed the fingerprint of a flawed procedure in the data. Specifically, the neutron data of Jones had low statistics and the deviation of the points from background was positively correlated with the uncertainty on each point. It is easy for an experimenter to obtain such an effect by watching the data come in and stopping when there appears to be a problem of some sort that is interfering with the effect one hopes to see. With Daniel Krakauer, Stuart published the analysis (1990) and also built a computer game that circulated widely in the community. Players were instructed to stop the data provided by a random-number generator when it looked like a positive deviation from the average was going away. The resulting data sets bore an uncanny resemblance to the one published by Jones.

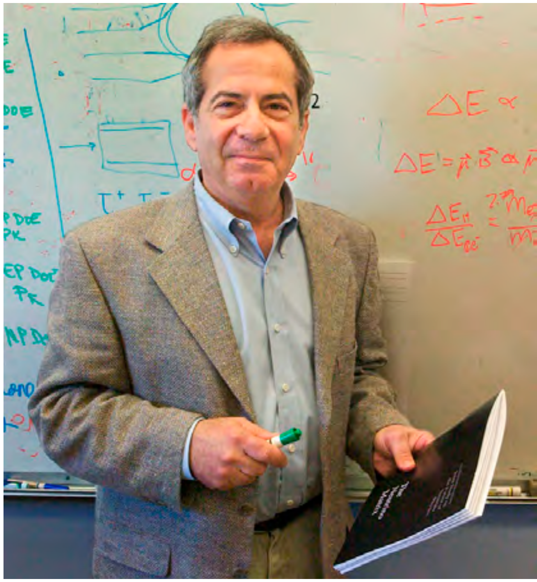


Figure 3. In this photo, Stuart is holding a copy of *The Neutrino Matrix.*

With the success of his research at Argonne and a desire to strengthen contact with students, Stuart accepted in 1987 a joint position as professor in the Enrico Fermi Institute of the University of Chicago. Four years later, he was lured back to UC, Berkeley, with an offer of a professorship on campus and a joint appointment at Lawrence Berkeley National Laboratory, and for a time he was occupying four prestigious positions in nuclear physics. Increasingly, the community turned to Stuart for advice and leadership. He became chair of the American Physical Society (APS) Division of Nuclear Physics (DNP) in 1998. In 2001, he initiated a successful series of joint meetings of the DNP with the Physical Society of Japan, held in Hawaii. He would complain of the advance work needed during "brutal Hawaiian winters" to prepare for these meetings. In the same year Stuart was elected to the National Academy of Sciences (NAS) and was appointed to the Luis Alvarez Memorial Chair in Experimental Physics at Berkeley. In 2006 he was named a fellow both of the American Academy of Arts and Sciences and of the American Association for the Advancement of Science. The APS awarded him the Tom W. Bonner Prize in 2007 "for his contributions to neutrino physics and the study of weak interactions, in particular for his leading role in the KamLAND experiment, as well as for his work on precision measurements of the beta decay of the neutron." An author of many influential reports, Stuart was most proud of *The Neutrino Matrix* volume that summarized the APS *Multidivisional Study on Neutrino Physics* of 2004, a study he cochaired with Boris Kayser. He also served as cochair with Ani Aprahamian of the NAS Committee on the Assessment of and Outlook for Nuclear Physics, which issued the *2010 NAS Decadal Report on Nuclear Physics*.

Stuart's final two decades at Berkeley were a productive and rewarding time for him. He divided his research time between fundamental symmetries experiments on the local 88-inch cyclotron and large collaborative experiments elsewhere.

Just as neutrons can be polarized and studied as they decay, so is it possible to polarize radioactive atoms in order to explore the nature of the weak interaction. Stuart was an early adopter of lasers to trap and polarize radioactive nuclei for fundamental-interaction experiments, and ^{21}Na was the focus of the program because of the ease with which it could be produced and trapped for study. The magneto-optical trap (MOT) for the experiment had an intriguing and beautiful shape, with magnetic coils and optical windows for laser beams. After his death, the first MOT that he built became the funerary urn for Stuart's ashes.

Another experiment that took advantage of the cyclotron's beams was a study of the beta decay of ^{10}C. It is one of a class of "superallowed" nuclear decays that collectively provides the most precise data on the Cabibbo angle, a measure of the rotation, or misalignment, of the strong and weak interactions between quarks. The origin of this misalignment is still a mystery and lies outside the standard model. It had been known for more than 20 years that the key decay to measure was ^{10}C, because it is the least affected by Coulomb and nuclear corrections, but the relevant branch is weak and the measurement fraught with experimental difficulty. Stuart devised an ingenious way to do the measurement—with internal calibrations that removed most of the systematic uncertainties. After many years of improving the technique with his colleague Brian Fujikawa, the final precision they obtained (1999) was good—but still not a challenge to the world average for the parameter measured with this and other nuclei.

The search for neutrino oscillations was poised to make the transition to discovery in the last few years of the 20th century. By 1997 there were indications from experiments that the solar neutrino problem could not be explained by astrophysics and that new neutrino physics was required. Experiments with water-based Cherenkov detectors built to search for proton decay were yielding puzzling results for what should have been a straightforward background process—the interaction of atmospheric neutrinos. Only about half the expected number of muon-flavor interactions were being seen, whereas the number of electron-flavor interactions came out right. Then, in 1998, the Super-Kamiokande detector at the Kamioka mine in Japan, a huge water-based Cherenkov detector, gave conclusive evidence for neutrino oscillations: a characteristic path-length dependence for the survival of atmospheric muon neutrinos produced on the other side of the planet.

Physicist Atsuto Suzuki noticed that Kamioka happened to be near the center of a rough circle formed by dozens of Japanese power reactors. The radius of this circle, 180 km, and the typical energy of electron (anti) neutrinos from reactors, meant that one particular choice of neutrino-oscillation parameters that could explain the solar neutrino problem would also give a pronounced signature in a suitable detector in Kamioka. Visiting the area in 1997, Giorgio Gratta began a collaboration with Suzuki and gathered several U.S. groups to participate in building a liquid scintillator detector at the site. Stuart became American cospokesman with Gratta in 1998, bringing his Berkeley group into the collaboration, and they worked successfully to interest the U.S. Department of Energy (DOE) in providing the necessary support. Completed in a relatively short time, the project, called the Kamioka Liquid Scintillator Antineutrino Detector (KamLAND), would turn out to be a stunning success.

In 2001 the solar-neutrino problem was resolved in favor of neutrino flavor change by the Sudbury Neutrino Observatory in Canada. The SNO detector showed definitively that electron neutrinos did indeed undergo flavor change, but it could not distinguish between three possible choices for the oscillation parameters. In 2003 KamLAND narrowed the choice to a single possibility, the "large-mixing-angle" solution. With more data, the collaboration was later (2008) able to display, at Stuart's urging, the results in a dramatic plot that revealed for the first time the oscillation phenomenon directly. The detector was capable of detecting antineutrinos from radioactive elements inside Earth as well, and did so.

The success of these experiments focused attention on the one remaining unknown parameter in neutrino flavor-oscillation physics, a parameter called θ_{13}, which essentially describes the amount of electron flavor mixing with other flavors over relatively short baselines. The parameter has special importance in neutrino physics because it must be nonzero in order to determine whether neutrinos respect the symmetry CP (equivalently, time-reversal invariance). Violation of CP symmetry by neutrinos would open a promising avenue for explaining why the universe contains mostly matter, and not much antimatter.

Determining θ_{13}, should have been a relatively easy step, given the short baseline needed, but the parameter was already known to be small. Measuring it would be an experimental *tour de force*. Stuart began to explore a site in California, at Diablo Canyon, but at the end of 2003 the project was declined by the utility that owned the reactors there. Attention turned to offshore sites: Daya Bay near Hong Kong, a site in South Korea, and one near the French-Belgian border. Enthusiastic interest by the Chinese government was met with equal enthusiasm in the United States, and the Daya Bay project was launched, as were the other two. The Berkeley physicists had much to contribute in light of their experience, and Stuart played an important role through 2004 in laying the groundwork for the experiment, but at some point he took exception to the Chinese approach. In turn, the Chinese leadership took offense and a serious rift developed. It eventually fell to Stuart's former fellow graduate student, Steven Chu, then director of the Lawrence Berkeley National Laboratory, to ask Stuart to step down from the collaboration and not provide direction to any other American physicists remaining in Daya Bay. It was in effect a denunciation, as well as a dilemma that was difficult for Stuart's colleagues to face. Careers, after all, were in the balance. Some went along, but others refused. Stuart tried to be philosophical about the situation, but in fact he was genuinely hurt.

All three projects were scientifically very successful, and θ_{13}, went from being the unknown mixing angle to the most precisely determined mixing angle. It turned out to be relatively large, almost at the upper limit set by a previous generation of experiments. The determination of this parameter is decisively important, placing within reach the goal of determining whether neutrinos are indifferent to the arrow of time.

Stuart also was active in other projects too numerous to mention here. The last major research initiative that Stuart undertook, the one on which he was working at the time of his death, was the search for neutrinoless double beta decay—the only practical means for deciding whether the neutrino is its own antiparticle or if neutrinos and antineutrinos are fundamentally distinct. Certain nuclei are stable against single beta decay but can decay by the simultaneous emission of two electrons and two (anti)neutrinos. If neutrinos and antineutrinos are the same, then a neutrino emitted may be instantaneously reabsorbed, and only the electrons are left to carry away the available energy. A handful of such cases are amenable to experimental study. A long tradition of research

Figure 4. Portrait of Stuart by his sister, Ina.
(Courtesy Joyce Freedman.)

into low-temperature calorimetric methods of measuring nuclear decays existed in Milan, Italy, led by Ettore Fiorini, and when he and his team sought to increase the scale of their ^{130}Te double-beta-decay detector from a few kilograms to hundreds of kilograms, they invited American groups to join. Stuart became the U.S. spokesman for this project, CUORE, and, as he had done so effectively in other cases, engaged the interest both of the U.S. DOE and National Science Foundation. When he died, the experiment was making good progress toward construction of a complete tower of ultrapure TeO_2 crystals, the first of many for the scaled-up detector.

Stuart enjoyed research and teaching, but most of all he enjoyed working with students and postdocs. His Berkeley students were Jason Amini, Thomas Banks, Christopher Bowers, Jason Burke, Daniel Dwyer, Laura Kogler, Laura Lising, Zhengtian Lu, Justin Mortara, Thomas O'Donnell, Mary Rowe, Nicholas Scielzo, Jason Stalnaker, Lindley Winslow, and Wesley Winter.

A modest man, Stuart wrote at the time of his election to the National Academy of Sciences:

> *I am an experimental physicist interested in understanding the nature of the fundamental forces and the basic composition of subatomic matter. I enjoy the experimental challenge of high-precision experiments exploiting atoms and nuclei as laboratories for studying fundamental questions. Despite their complexity, nuclei and atoms reflect the basic symmetries of the underlying physics governing the interactions among the more fundamental quarks and leptons. Much of my work involves searches for unexpected phenomena, new particles or interactions that might indicate a shortcoming in the current theoretical description.*
>
> *Recent experiments in my laboratory exploit new methods of atom and ion manipulation to make very precise measurements in nuclear beta decay. These experiments question the basic structure of the weak interaction. We are also conducting an experiment with a massive underground reactor antineutrino detector, which addresses basic questions about the masses of the neutrinos.*

Stuart passed away on November 10, 2012, at the age of 68, from complications of amyloidosis. He was in Santa Fe, NM, attending a conference on the uses of ultracold neutrons for fundamental-symmetry research, surrounded as he was throughout his life by friends. His death came unexpectedly to most people, as Stuart had kept the condition largely to himself. He left behind a loving family—his sister Ina Scheid, wife Joyce, son Paul, daughter-in-law Emily Van Allen Freedman, and grandchildren Evie and Jonah—a legion of friends and admirers, and proof that integrity can travel hand-in-hand with achievement.

Selected Bibliography

1972 With J. F. Clauser. Experimental test of local hidden-variable theories. *Phys. Rev. Lett.* 28:938–941.

1973 With E. Wigner. On Bub's misunderstanding of Bell's locality argument. *Found. of Phys.* 3:457–458.

1975 With F. P. Calaprice, W. C. Mead, and H. C. Vantine. Experimental study of weak magnetism and second-class interaction effects in the b decay of polarized ^{19}Ne. *Phys. Rev. Lett.* 35:1566–1570.

1977 With F. P. Calaprice, B. Osgood, and W. C. Thomlinson. Test of time-reversal invariance in the beta decay of ^{56}Co. *Phys. Rev. C* 15:381–389.

1982 With A. Marini et al. Search for exclusive free-quark production in e+e- annihilation. *Phys. Rev. Lett.* 48:1649–1652.

With A. Marini et al. Experimental limits on quarks, tachyons, and massive particles in cosmic rays. *Phys. Rev. D* 26:1777–1780.

1983 With G. T. Garvey, M. Kroupa, J. Napolitano, and J. Worthington. A liquid scintillator cosmic ray active shield. *Nucl. Instrum. and Meth. in Phys. Res.* 215:71–77.

1987 With J. Napolitano and J. Camp. Beta and neutrino spectra in the decay of ^{8}B. *Phys. Rev. C* 36:298–302.

1988 With P. Bopp, E. Klemt, J. Last, H. Schutze, and D. Dubbers. The superconducting neutron decay spectrometer PERKEO. *Nucl. Instrum. and Meth. in Phys. Res. A* 267: 436–447.

With E. Klemt, P. Bopp, L. Hornig, J. Last, D. Dubbers, and O. Scharpf. The beta-decay asymmetry of the neutron. *Z. Phys. C* 37:179-189.

With J. Last, M. Arnold, J. Döhner, and D. Dubbers. Pulsed-beam neutron-lifetime measurement. *Phys. Rev. Lett.* 60:995–998.

1989 With F. L. H. Wolfs, J. E. Nelson, M. S. Dewey, and G. L. Greene. Measurement of the ^{3}He(n,g) ^{4}He cross-section at thermal neutron energies. *Phys. Rev. Lett.* 63:2721–2724.

1990 With D. Krakauer. Biases in cold fusion data. *Nature* 343:703–703.

1993 With B. K. Fujikawa et. al. Limits on neutrino oscillations from anti-electron-neutrino appearance. *Phys. Rev. D* 47:811–829.

With J. L. Mortara, I. Ahmad, K. P. Coulter, B. K. Fujikawa, J. P. Greene, J. P. Schiffer, W. H. Trzaska, and A. R. Zeuli. Evidence against a 17-keV neutrino from ^{35}S beta decay. *Phys. Rev. Lett.* 70:394–397.

1999 With B. K. Fujikawa, S. J. Asztalos, R. M. Clark, M.-A. Deleplanque-Stephens, P. Fallon, J. P. Greene, I.-Y. Lee, L. J. Lising, A. O. Macchiavelli, R. W. MacLeod, J. C. Reich, M. A. Rowe, S.-Q. Shang, F. S. Stephens, and E. G. Wasserman. A new measurement of the strength of the superallowed Fermi branch in the beta decay of ^{10}C with GAMMASPHERE. *Phys. Lett. B* 449:6–11.

2003 With K. Eguchi et al. First results from KamLAND: Evidence for reactor anti-neutrino disappearance. *Phys. Rev. Lett.* 90:021802-1–021802-6.

With W. T. Winter, K. E. Rehm, I. Ahmad, J. P. Greene, A. Heinz, D. Henderson, R. V. F. Janssens, C. L. Jiang, E. F. Moore, G. Mukherjee, R. C. Pardo, T. Pennington, G. Savard, J. P. Schiffer, D. Seweryniak, G. Zinkann, and M. Paul. Determination of the ^{8}B neutrino spectrum. *Phys. Rev. Lett.* 91:252501-1–252501-4

2004 With B. Kayser and other members of the APS Multi-Divisional Neutrino Study. *The neutrino matrix.* Washington, DC: American Physical Society. Available online at www.aps.org/policy/reports/multidivisional/index.cfm, accessed on May 16, 2014.

2008 With S. Abe et al. Precision measurement of neutrino oscillation parameters with KamLAND. *Phys. Rev. Lett.* 100:221803-1–221803-5.

2012 With T. E. Chupp et al. Search for a T-odd, P-even triple correlation in neutron decay. *Phys. Rev. C* 86:035505-1–035505-22.

2014 With D. E. Artusa et al. Searching for neutrinoless double-beta decay of ^{130}Te with CUORE. *arXiv* 1402.6072.