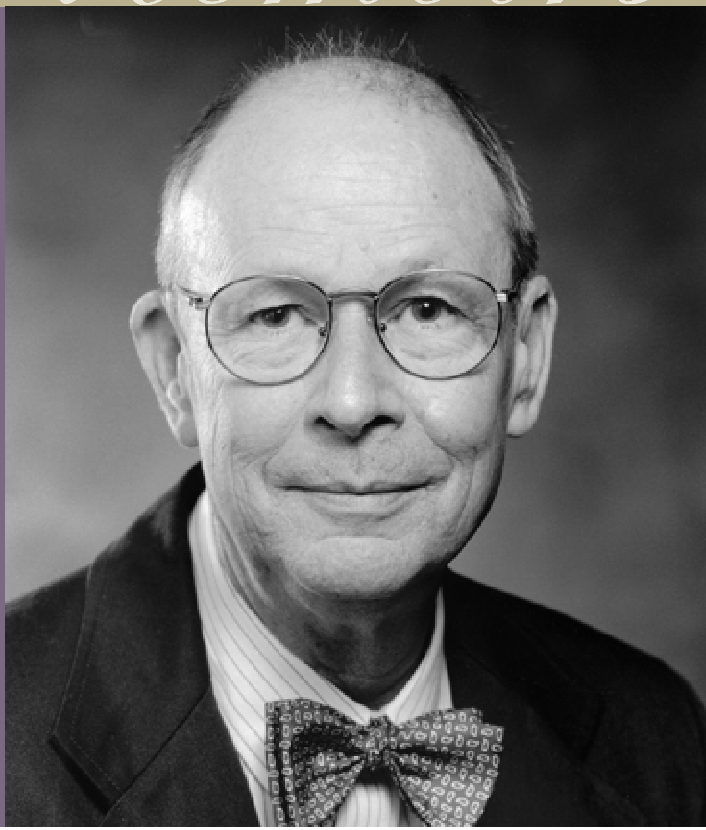
Robert C. Richardson

1937–2013

BIOGRAPHICAL *Memoirs*



A Biographical Memoir by
J. D. Reppy and D. M. Lee

NATIONAL ACADEMY OF SCIENCES

ROBERT COLEMAN **RICHARDSON**

June 26, 1937–February 19, 2013

Elected to the NAS, 1986

By J. D. Reppy and D. M. Lee

Robert C. Richardson was a highly skilled and accomplished experimental physicist specializing in low-temperature phenomena. He earned B.S. and M.S. degrees in physics in the late 1950s at Virginia Polytechnic Institute (Virginia Tech) and a Ph.D. in low-temperature physics at Duke University in 1966. At Cornell University in 1974 Richardson and his group discovered the antiferromagnetic phase transition of solid helium-3 at a temperature near 1 millikelvin (mK). Later, with his expertise in nuclear magnetic resonance and cryogenics, he pioneered studies of the transfer of nuclear magnetism between liquid helium-3 and the nuclei of fluorine atoms embedded in tiny fluorocarbon beads. He shared the 1996 Nobel Prize in Physics for the discovery, with his co-workers, of the superfluid phases of liquid helium-3.

Richardson was a dedicated teacher and was particularly remembered for his stimulating public lectures, complete with amusing demonstrations of low-temperature phenomena. Science policy was an area in which Richardson made substantial contributions, both at the university and national level.

Robert Colman "Bob" Richardson was born in Washington, D.C., on June 26, 1937, and grew up in nearby Arlington, Virginia. His early interests tended toward outdoor pursuits—hiking, camping, and a strong interest in birds. In later life Bob took up gardening with a similar intensity. Following his graduation from Arlington's Washington and Lee High School in 1954, Bob enrolled at the Virginia Polytechnic Institute (now also officially known as Virginia Tech), where he majored in physics and earned both B.S. and M.S. degrees.

During his time at VPI Bob worked in the laboratory of Professor Tom Gilmer. His M.S. project was a measurement of the lifetime of photo-excited carriers in germanium. In his work on this project, he acquired important basic laboratory skills, including machining, soldering, and assembly of simple electronic circuits. Following his years at Virginia Polytechnic, he served six months' active army duty at Aberdeen Proving Ground, Maryland, as an officer in the Quartermaster Corps before enrolling in the physics Ph.D. program at Duke University. His army experience provided Bob with some of the organizational skills he displayed in his later physics career.

Low-temperature physics at Duke

The physics department at Duke was well known for research in experimental and theoretical low-temperature physics. Fritz London established a grand tradition there in this field with his realization that superfluidity in helium-4 (^{4}He) and superconductivity in metals were both manifestations of quantum mechanics on a macroscopic scale. He also supported the idea—put forth as well by fellow physicist László Tisza—that Bose-Einstein condensation was involved in the superfluidity of liquid ^{4}He. Later, William Fairbank joined Duke's department and established a world-renowned program in experimental low-temperature physics. Walter Gordy, an expert on magnetic resonance, was also on the faculty and provided useful advice to the low-temperature group.

At this time (the early 1960s) helium-3 (^{3}He) was starting to become available for low-temperature physics research. The nucleus of the ^{3}He atom has a spin of 1/2 and therefore a nuclear magnetic moment, which makes possible nuclear magnetic resonance (NMR) studies of liquid ^{3}He. Fairbank and his students made key discoveries with this technique combined with adiabatic demagnetization of a paramagnetic salt to achieve temperatures below 1K. They observed the onset of Fermi liquid behavior in pure ^{3}He and the phase separation of liquid ^{3}He-^{4}He mixtures into a ^{3}He-rich phase and a ^{4}He-rich phase. This latter discovery was essential to the success of the dilution refrigerator, which allowed samples to be cooled to a few millikelvin for protracted periods of time.

Eventually Fairbank left Duke to take a position at Stanford. Duke then hired Horst Meyer as the new head of the low-temperature program. Bob Richardson soon became a member of this group and performed pulsed NMR experiments on solid ^{3}He for his 1966 Ph.D. dissertation. His research under Meyer involved studies of nuclear spin interactions in solid ^{3}He. The program benefited from participation by Earle Hunt, who was a postdoctoral research associate in the group at the time. Hunt's expertise in spin-echo techniques was extremely helpful (and he and Bob became lifelong friends). The observed nuclear-spin interactions were expected to give rise to nuclear-spin ordering at much lower temperatures.

During his years at Duke, Bob met his future wife, Betty McCarthy, who had been a physics major at Wellesley College. Betty was a fellow graduate student in physics at the time. They were married in 1962. Their two children, Jennifer and Pamela, were born in Durham in 1965 and 1966, respectively. After completing his dissertation in 1965, Bob remained at Duke for a while as a research associate.

Physics research at Cornell

In the fall of 1966 Bob moved to the low-temperature group at Cornell University's Laboratory of Atomic and Solid State Physics as a research associate, and in 1968 he joined the Cornell physics faculty as an assistant professor. An interdisciplinary laboratory of the Defense Department's Advanced Research Projects Agency (ARPA) provided Cornell with additional funding that made it possible to support the research of a larger low-temperature faculty, which, after Bob's appointment, consisted of him and we two authors of this memorial bio.

At the time Bob joined the group, a program was just getting under way to cool ^{3}He to extremely low temperatures via a method conceived by Isaak Pomeranchuk, a Soviet theorist. The method involved adiabatically compressing ^{3}He from the liquid into the solid phase. ^{3}He exhibits a minimum in its melting curve at a temperature of about 0.3 K and a pressure of 29 atmospheres. The Clausius-Clapeyron equation tells us that below this temperature ^{3}He acquires a negative latent heat. Thus, compressing from the liquid into the solid phase will result in cooling below 0.3 K. During this process the sample cell will contain a mixture of liquid and solid ^{3}He. Typically, the cell is precooled to 20 mK with a dilution refrigerator. At the time of these experiments dilution refrigerators were not commercially available, so it was necessary to design and construct the one at Cornell.

To achieve Pomeranchuk cooling, an important obstacle had to be overcome. Such cooling could not occur until the temperature of the contents of the Pomeranchuk cell was below the minimum melting pressure temperature, but it was not possible to pressurize the sample via a connection to an external gas-handling system, as the capillary tube connecting the cell to this gas-handling system would be blocked with solid ^{3}He.

A second problem then arose. The only hydraulic fluid capable of driving the system at such temperatures was liquid ^{4}He. But the melting pressure of ^{4}He is 25 atmospheres, so direct compression with this hydraulic fluid, separated from the ^{3}He by a thin diaphragm, could not work. Only if this diaphragm was prestressed by liquid ^{3}He could this problem be overcome. Yu. D. Anufriyev was the first to cool ^{3}He via the Pomeranchuk method, working at the Institute for Physical Problems (now the Kapitza Institute) in Moscow. He used a stressed diaphragm technique to overcome the blocked capillary problem. Subsequently John Wheatley's group used a stressed diaphragm to achieve Pomeranchuk cooling at the University of California, San Diego.

Researchers at Cornell took another approach. They decided to employ a flexible (sylphon) bellows technique to compress the liquid ^{3}He into the solid phase. In the final configuration they gained the pressure amplification required by connecting a large-diameter bellows containing the ^{4}He by a rigid rod to a smaller-diameter bellows containing the ^{3}He sample. This arrangement was basically a hydraulic press, which allowed compression of the ^{3}He to well over 30 atmospheres. The advantage of this method was that it allowed the possibility of self-cooling, thereby conveniently cooling large volumes of ^{3}He along the melting curve.

Bob played a very active role in all of the preparations for Pomeranchuk cooling. A group of dedicated graduate students worked on the project, and Bob was an excellent mentor for them. He spent many evenings around the laboratory and was always available for consultations and hands-on help with the equipment.

James Sites was the first student at Cornell to make use of Pomeranchuk cooling. His Ph.D. dissertation involved continuous-wave NMR studies of Pomeranchuk-cooled solid ^{3}He. (Note that there was always a mixture of liquid and solid ^{3}He in the sample cell.)

The nuclear susceptibility of the liquid ^{3}He was small compared with that of solid ^{3}He as a result of the Pauli paramagnetism associated with the Fermi-Dirac behavior of liquid ^{3}He first seen by William Fairbank's group in the 1950s. Sites's experiment revealed that the temperature dependence of the nuclear magnetic susceptibility of the solid was consistent with the eventual onset of antiferromagnetic ordering in solid ^{3}He at lower temperatures, but the actual signature of nuclear ordering was not observed.

The Pomeranchuk cell that Sites used was not able to cool to temperatures close to 1 mK due to a completely unexpected design flaw that allowed solid ^{3}He to be trapped in the bellows convolutions. As the bellows was pushed down, the trapped solid ^{3}He was crushed, leading to unwanted heating.

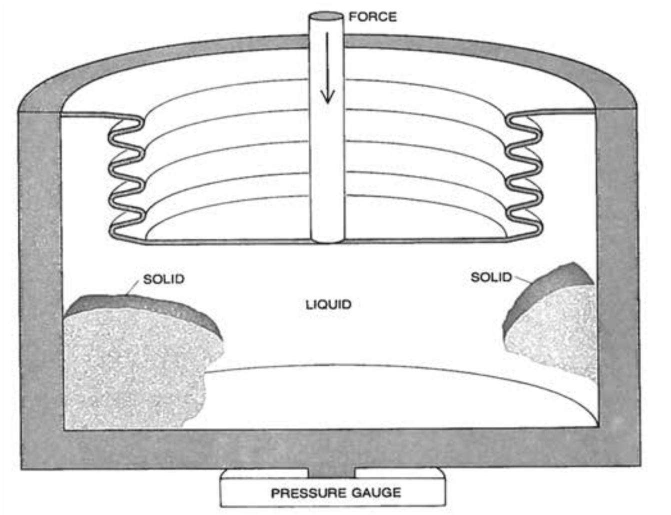


Figure 1:
Pomeranchuk Cell: Pomeranchuk (compressional) cooling can provide extremely low temperatures because the conversion of liquid to solid helium-3 will lead to an absorption of heat when the starting temperature is below 0.3 Kelvin. Precooling with a dilution refrigerator to 0.02 Kelvin allows one to reach temperatures below 0.001 degrees Kelvin. When pressure was applied to a cell containing liquid helium 3 at its freezing pressure, the liquid would start converting to solid helium-3, thus cooling the contents of the cell. At the end of the process a mixture of solid and liquid and solid was present in the cell. Anomalous pressure behavior was monitored via a sensitive pressure gauge. (Figure adapted from N. D. Mermin and D. M. Lee, *Scientific American* 235, 56 (1976), 56-71, page 67.)

To overcome this problem a second graduate student, Douglas Osheroff, took on the task of designing a new Pomeranchuck cell while he was recovering from a skiing injury. In this cell the bellows expanded and the convolutions opened up as the bellows pushed into the ^{3}He region, decreasing the volume available for the ^{3}He (See Figure 1) A third graduate student, Linton Corrucini performed pulsed nuclear magnetic resonance on liquid ^{3}He in a separate cell thermally connected to this Pomeranchuk cell. The experiment revealed anomalous spin diffusion resulting from Fermi liquid behavior, which had previously been predicted by Leggett and Rice. Bob Richardson's expertise in pulsed NMR and his role in interpreting the experimental data were essential ingredients in the success of these experiments. At some point Bob made the key suggestion that it was important to measure the melting pressure as solidification of the ^{3}He took place. As a result of this suggestion, the students installed a sensitive capacitance pressure gauge, first developed by Straty and Adams at the University of Florida (See Figure 1).

One night in late November 1971, while Osheroff was testing his Pomeranchuk cell, he noticed small anomalies in the melting-curve pressure-vs.-temperature readings as displayed on a chart recorder. A steady force was applied (via the liquid ^{4}He in the upper bellows) which resulted in a decrease in temperature due to the Pomeranchuk effect, typically measured by an NMR thermometer consisting of platinum wires. An abrupt change in the slope of the pressure-vs.-time curve took place at about 2.7 mK. The change was attributed to a specific heat maximum. As the Pomeranchuk cooling process was reversed by reducing the pressure, a mirror image of this pressure-vs.-time signature was observed at the same value of pressure seen during the cooling process.

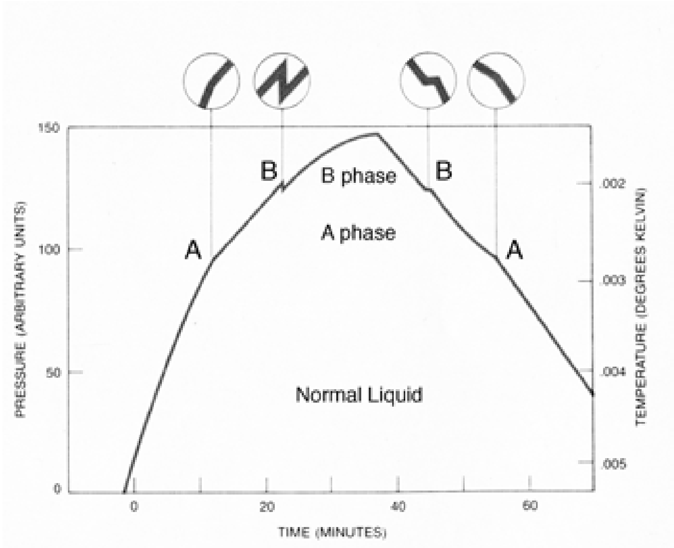


Figure 2: Small pressure anomalies appeared in the pressure-vs.-time signature as the pressure in the Pomeranchuk cell was slowly increased to a maximum and then slowly decreased. The temperatures were obtained from the nuclear magnetic susceptibility of a small bundle of thin platinum wires. The observed discontinuities during pressurization signaled phase transitions from normal liquid helium to first the A phase and next the B phase of superfluid helium-3, followed by a reversal of the process as the pressure was lowered and the cell warmed. (Figure adapted from N. D. Mermin and D. M. Lee, *Scientific American* 235, 56 (1976), 56-71, page 67.)

The point where the slope change took place is labeled A in Figure 2. A second even more intriguing anomaly showed up at point B in the figure. As the pressure in the ^{3}He cell rose and concurrently the temperature was lowered, a sudden small pressure drop occurred. This point was labeled point B. When the pressure was lowered, leading to a warming of the sample, this feature appeared at a slightly higher temperature (lower pressure) as a small plateau or hesitation in warming. The plateau was thought to correspond to a latent heat, whereas the sudden drop seemed to be a result of a supercooling transition. Feature B therefore was interpreted as a first-order transition.

This was an exciting development. Bob remarked "We have a tiger by the tail." There were countless debates about the interpretation of these features. Since the cell contained a mixture of liquid and solid ^3He, were these anomalies associated with the liquid or solid state? A great deal of discussion ensued, since it was important to have the correct interpretation for these effects. At the time of the observations, which began in late November 1971, there was a great deal of pessimism regarding the possibility of ever observing a superfluid transition at any reasonable temperature. Liquid ^3He is a Fermi liquid, so any transition to a superfluid phase would have to involve Cooper pairs. Pitaevskii realized that the short-range repulsive forces between ^3He atoms would rule out s-wave pairing such as that discussed by Bardeen, Cooper, and Schrieffer for electrons in metals. Thus, higher-order relative-angular-momentum pairs were required.

Some members of the theory community had all but given up hope that the superfluid ^3He phase transitions would be found at a reasonably achievable temperature. Furthermore, John Wheatley, the acknowledged world leader in liquid ^3He research, had conducted some experiments at the University of California, San Diego in the range of 2 mK on liquid ^3He at low pressure using adiabatic demagnetization employing a dilute paramagnetic salt (cerium magnesium nitrate) with negative results. Therefore after much discussion at Cornell, the decision was made to attribute the bizarre effects to solid ^3He. As it turned out this decision was diametrically wrong. In retrospect, the rapid supercooling seen at point B was certainly more in line with liquid behavior.

Fortunately an experiment to perform nuclear magnetic resonance on the mixed liquid-and-solid sample in the Cornell Pomeranchuk cell was already in the pipeline. An NMR coil was placed in the cell vertically along the cell axis. A large electromagnet supplied a horizontal magnetic field. By arranging for a field gradient to be applied, different locations in the cell would correspond to different NMR frequencies or, alternatively, to different magnetic fields when a field sweep was applied (see Figure 3). This was one of the first physics experiments to utilize magnetic resonance imaging (MRI). In fact Paul Lauterbur, who (along with Sir Peter Mansfield) later won the Nobel Prize in medicine, visited the Cornell laboratory when these experiments were in progress. The idea of the Cornell experiment was to locate the presence of solid ^3He by looking for regions in the cell with a very large nuclear susceptibility. If no solid were present in a region, only a small liquid ^3He NMR signal would be observed. As it turned, out Mother Nature was extremely cooperative. Solid ^3He tended to form at the ends of the NMR coil, leaving only a liquid ^3He signal emanating from the central part of the coil.

Doug Osheroff was going over the NMR data late one night when he noticed a startling result. The liquid NMR signal suddenly dropped by a factor of approximately 2 when

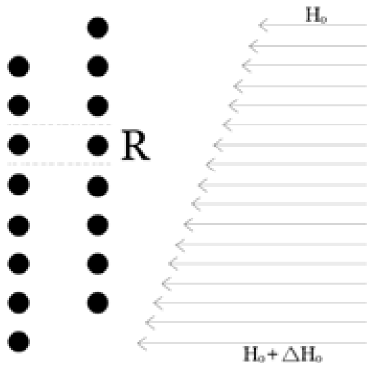


Figure 3: Schematic showing an NMR coil assembly placed inside the cell for the helium-3 NMR absorption studies. Arrows to the right correspond to the applied magnetic field during position profile experiments, and the layer of the helium-3 at resonance in the non-uniform magnetic field is indicated by the letter R.

the cell cooled through the B transition. In the wee hours of the morning he telephoned his colleagues on the experiment—a wonderful late-night phone call! This observation showed that the B transition was in fact associated with the liquid and was probably a transition into a superfluid phase. Bob had always been a firm believer in serendipity, and this result seemed like a "dream come true."

Next the field gradient was removed. As Osheroff, Bob and Lee watched the NMR traces, they were surprised to see the liquid signal shift away from the solid signal starting just below the A transition temperature. Based on this observation they associated the A and B transitions with two separate superfluid phases of liquid ^3He, the A Phase and the B phase (see Figure 2). The A phase experiment was repeated at a number of different magnetic fields. Professor Bob Silsbee at Cornell suggested that the data be plotted in the form $\omega^2(\text{liquid}) - \omega^2(\text{solid}) = \Omega^2(T)$, where Ω is a function of the temperature. The data fit this formula beautifully. It almost seemed as if there were an internal magnetic field perpendicular to the applied field, raising the possibility that a longitudinal resonance signal might be observed.

Shortly after these results were obtained, Bob visited the University of Sussex in Brighton, U. K. While there, he discussed the data with theorist Sir Anthony "Tony" Leggett. Tony immediately set to work on the problem and soon came up with the idea of spontaneously broken spin-orbit symmetry, which could be associated with superfluid phases of ^3He.

Possible candidates for p-wave superfluidity had been put forth by Anderson and Morel (later joined by Brinkman) as well as by Balian and Werthamer. Tony Leggett later developed a comprehensive theory of the spin dynamics of these phases and showed that the A- and B-phase NMR results were consistent with the Anderson-Brinkman-Morel and Balian-Werthamer proposals. Furthermore he confidently predicted a longitudinal resonance, which later was first observed by Doug Osheroff, then at Bell Laboratories, and then by the Cornell group.

The nuclear magnetic ordering transition in solid ^{3}He was yet to be discovered. Bob, along with his student William “Bill” Halperin and co-workers Charles Archie, Finn Rasmussen, and Robert Buhrman, developed a specialized Pomeranchuk cell especially for this purpose. The effort met with great success. The magnetic transition was observed to occur at about 1 mK. For Bob this was the successful end of a long search and was a truly satisfying moment.

The new phase transitions discovered at Cornell set off a world-wide effort to determine the nature of these phases. Cornell offered an excellent atmosphere for carrying out such research. Professors and students engaged freely with each other in joint experiments. This strong spirit of cooperation led to many significant discoveries of the properties of the new phases of superfluid ^{3}He. Examples of these collaborations in which Bob participated included further NMR studies of superfluid ^{3}He and the use of ultrasound to discover collective modes of superfluid ^{3}He—with David Lee along with his students and postdocs—and studies of the superfluid flow properties of superfluid ^{3}He with John Reppy and his students and postdocs.

Although Pomeranchuk cooling had served a useful purpose during the period of discovery, it had disadvantages. In particular, measurements inside the Pomeranchuk cell were restricted to the melting pressure, and researchers could not produce the lowest values of temperature through indirect cooling of a separate sample cell due to poor heat transfer between the experimental cell and the Pomeranchuk cell. Therefore, shortly after the discovery experiments, the decision was made to install a nuclear adiabatic demagnetization set-up to overcome these difficulties. They constructed a metallic copper nuclear stage, consisting of an array of thin copper slabs to minimize eddy-current heating during demagnetization. Bob played a leading role in the design and construction of this facility. Later, nuclear demagnetization set-ups using $PrNi_5$ (praesodimium nickel-5) for the nuclear stage were installed elsewhere in the Cornell labs. In both cases, use of a dilution refrigerator was required for pre-cooling the stages to temperatures of the order of 10 mK in magnetic fields greater than about 7 tesla. It became possible via nuclear adiabatic demagnetization to cool ^{3}He to temperatures well below 1 mK.

John Goodkind and his graduate students D. L. Solfa and J. M. Dundon first performed nuclear cooling of liquid ^{3}He at the University of California, San Diego in 1973. Later the Helsinki University of Technology (now Aalto University) built an efficient nuclear cooling facility. Olli Lounasmaa was the leader of a large and successful group there that specialized in low-temperature physics. Since the mid-1960s there were good relations between the Helsinki low-temperature group and the Cornell group. In the mid-1970s Bob spent a very enjoyable and productive sabbatical year with this group. During his year in Helsinki, Bob participated in experiments to study the mobility of negative ions in superfluid ^{3}He and in NMR experiments on textural defects in superfluid ^{3}He A.

Starting in the 1980s while still maintaining an involvement with superfluid ^{3}He, Bob initiated a program to study surface relaxation between liquid ^{3}He, a thin intermediate surface layer of solid ^{3}He, and eventually a solid-layer substrate containing fluorine nuclei. Bob, along with his student P. C. "Chris" Hammel, proposed a model in which the T1 relaxation time should be essentially independent of temperature. This model was by and large successful. The most spectacular result of this research program was the observation made by graduate student Larry Friedman, P. J. Millet, and Bob of cross-relaxation between the ^{3}He nuclei and the fluorine nuclei in the substrate. The fluorine was contained in one-micron-diameter fluorocarbon beads.

Bob was also the thesis advisor for Michael Rouckes, who was awarded his Cornell Ph.D. in 1985. Rouckes's work concerned the problem that at very low temperatures, a moving electron gas may no longer be in thermal equilibrium with the lattice due to the absence of phonons. He was able to determine the difference between the lattice temperature and the temperature of the "hot" electrons in a resistor by employing noise thermometry. He measured the noise spectrum through a technique involving the use of superconducting quantum interference detectors (SQUIDs).

Mark Freeman was one of Bob's last graduate students, receiving his Ph.D. in 1988. He used NMR and a torsional oscillator technique, originally developed by John Reppy, to characterize the behavior of superfluid ^{3}He in a confined geometry. Freeman trapped the ^{3}He sample between layers of mylar separated by 0.5-micron fluorocarbon beads. The NMR signals let him identify the superfluid phase, and the torsional oscillator measurements let him determine the superfluid density. The ^{3}He A phase NMR frequency shift, the superfluid density, and the superfluid transition were all in good quantitative agreement with the Ginzburg-Landau model, with the order parameter vanishing at the walls (the diffusive boundary condition). When Freeman added ^{4}He, it drastically modified the boundary condition, leading to specular scattering of the quasi-particles at the liquid ^3He – ^4He boundary, adjacent to the walls.

Bob had always felt that ultra-low temperatures should be made accessible to the larger community of condensed-matter physicists outside the traditional quantum fluid research area. He thus embarked on a program to design and construct a microkelvin laboratory at Cornell to accomplish this goal. Experiments performed in the early 1990s by Bob and co-workers Lois Pollack, Eric Smith, and Jeevak Parpia using this new facility included studies of cross-relaxation in nuclear electric quadrupole resonance (NQR) studies involving scandium nuclei.

In a separate set of experiments in this facility Bob and his group performed NQR studies on single crystals of the heavy fermion metal cerium copper-6 (CeCu6). They determined the spin lattice relaxation time T1 and NQR intensities for three different sites in the crystal (corresponding to three different NQR frequencies) at temperatures ranging from 200 mK to 2 mK.

These measurements marked the end of Bob's brilliant and productive scientific career. He retired from Cornell in 2008, at the age of 71. Over his long career he had received many honors. He was awarded the eighth Sir Francis Simon Memorial Prize of the (British) Institute of Physics in 1976, the 1981 Oliver Buckley Prize in Condensed Matter Physics of the American Physical Society, and the 1996 Nobel Prize in Physics, all with Douglas Osheroff and David Lee for the discovery of the superfluid phases of liquid ^3He.

Bob won John Simon Guggenheim fellowships twice, in 1975-76 and 1982-83. He became a fellow of the American Association for the Advancement of Science in 1981, a fellow of the American Physical Society in 1983, a member of the National Academy of Sciences in 1986, a foreign member of the Finnish Academy of Science and Letters in 1993, and a fellow of the American Academy of Arts and Sciences in 1995. In, 2001 he was made a member of the American Philosophical Society.

Teaching, administration, and science policy

In addition to his devotion to scientific discovery, Bob was a dedicated teacher. He enjoyed lecturing in the elementary physics courses at Cornell and in particular demonstrating various phenomena to his classes. He also gave fascinating public lectures with demonstrations involving high-temperature superconductors and other cryogenic phenomena. In addition he produced some stimulating instructional videotapes.

Following the tragic death of his daughter Pamela in 1994, of sudden heart failure, Bob, his wife, Betty, and Alan Giambattista embarked on a project to produce an introductory college physics textbook in her memory. At the time, Betty and Alan were senior lecturers in the Cornell Physics Department. Work on this project, which was intended to provide a scholarship in Pamela's name, helped Bob and Betty deal with the grief at the loss of their daughter. The book, *College Physics*, was published by McGraw-Hill in 2004, and has been quite successful.

For graduate-level learning Bob, Eric N. Smith, and 21 Cornell graduate students produced *Experimental Techniques in Condensed Matter Physics at Low Temperatures* (Addison-Wesley, 1988). This book, filled with practical suggestions and techniques, has been widely used by condensed-matter physicists in the United States and around the world.

From 1990 to 1996 Bob served as the director of the Laboratory of Atomic and Solid State Physics at Cornell. He was vitally interested in science policy, both on a university level and on a national level. Over the years he served on numerous boards and committees. For example, he was chair of the Physics Section of the National Academy of Sciences from 1989 to 1992. He was co-chair of the National Science Foundation Panel on Large Magnetic Fields from 1986 to 1988. During his tenure, the decision was made to establish the National High Magnetic Field Laboratory, now located in Florida at Tallahassee and Gainesville. In 1995 he served as chair of the Division of Condensed Matter Physics of the American Physical Society. He was appointed to the Duke University Board of Trustees in 1997.

In 1998 Bob was named vice-provost for research at Cornell, in 2004 senior vice-provost for research, in 2007 senior science adviser to the president of Cornell, and in 2008 senior vice-provost for research emeritus. In 2004, Bob became the founding director of Cornell's Kavli Institute, which has been devoted to studies of nanomaterials and also to developing new nanomaterials. Bob was highly regarded by the top administrators at Cornell for his clear thinking, his encyclopedic knowledge of federal funding agencies in Washington, and his enthusiasm for undertaking new initiatives in science and technology at the university. He was particularly excited about improving contacts between the biological and the physical sciences, which he felt would present opportunities for new synergies.

On the national scene, he was a member of an important National Academies committee on prospering in the global economy of the 21st century, chaired by Norman Augustine to address the importance of support for science in the United States. The committee published a highly influential report in 2008 entitled "Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future." This report had considerable impact on the attitudes of government leaders toward science as well as on the general public, since much of modern technology is based on fundamental scientific discoveries. The report also warns of the consequences of neglecting science and technology and the benefits of having a vibrant scientific and technological base in a society. A book based on the report, whose title is the same as that of the report, was published by the National Academies Press in 2007.

In summary

Bob made strong contributions to research, teaching, and science policy, tackling tasks with zest and vigor in all three areas. He was innovative in the laboratory as well as in the area of administration. He motivated his graduate students and led by example. Over his career he produced a record of scientific accomplishment with the ultimate reward being the 1996 Nobel Prize in physics. He was popular with students, friends, and colleagues. All of those who worked with Bob have fond memories of their association with him. He will be sorely missed.

SELECTED BIBLIOGRAPHY

1965 With E. Hunt and H. Meyer. Nuclear relaxation in solid helium-3 in the b.c.c. phase. *Phys. Rev.* 138:A1326-A1335.

1971 With A. Greenberg and W. Thomlinson. Isotopic impurity tunneling in solid ^{4}He. *Phys. Rev. Ltrs.* 27:179-183.

1972 With D. D. Osheroff and D. M. Lee. Evidence from melting pressure measurements for a phase transition in solid ^{3}He at 2.8 mK. *Phys. Rev. Ltrs.* 28:885-888.

With D. D. Osheroff, W. J. Gully, and D. M. Lee. New magnetic phenomena in liquid ^{3}He below 3 mK. *Phys. Rev. Ltrs.* 29:920-923.

1973 With D. T. Lawson, W. J. Gully, S. Goldstein, and D. M. Lee. Attenuation of zero sound and the low-temperature transitions in liquid ^{3}He. *Phys. Rev. Ltrs.* 30:541-544.

1974 With W. P. Halperin, C. N. Archie, R. A. Buhrman, and F. B. Rasmussen. Observation of nuclear magnetic order in solid ^{3}He. *Phys. Rev. Ltrs*. 32:927-930.

1975 With W. P. Halperin, C. N. Archie, and F. B. Rasmussen. Thermodynamic temperature scale derived from measurements of ^{3}He latent heat. *Phys. Rev. Ltrs.* 34:718-721.

1976 With A. I. Ahonen, J. Kokko, O. V. Lounasmaa, M. A. Paalanen, W. Schoepe, and Y. Takano. Mobility of negative ions in superfluid ^{3}He. *Phys. Rev. Ltrs.* 37:511-514.

1978 With D. M. Lee. Superfluid ^{3}He. In *The Physics of Liquid and Solid Helium, Part II*. Ed. K. H. Benneman and J. B. Ketterson. pp. 287-496. New York: Wiley.

1980 With R. W. Giannetta, A. Ahonen, E. Polturak, J. Saunders, E. K. Zeise and D. M. Lee. Observation of a New Sound Attenuation Peak in Superfluid ^{3}He-B. *Phys. Rev. Lett.* 45: 262-265.

1981 With L. J. Friedman and P. J. Millet. Surface relaxation of ^{3}He on small fluorocarbon particles. *Phys. Rev. Ltrs.* 47:1078-1081.

1984 With P. C. Hammel. Relaxation of nuclear magnetism of liquid ^{3}He in confined geometries. *Phys. Rev. Ltrs.* 52:1441-1444.

1988 With M. R. Freeman, R. S. Germain, and E. V. Thuneberg. Size effects in thin films of superfluid ^3He. *Phys. Rev. Lett.* 60:596-599.

1992 With L. Pollack, E. N. Smith, and J. M. Parpia. Novel low-temperature cross-relaxation in nuclear quadrupole resonance. *Phys. Rev. Lett.* 69:3835-3839.

1995 With L. Pollack, J. J. R. Hoch, C. Jin, E. N. Smith J. M. Parpia, D. L. Hawthorne, D. A. Geller, D. M. Lee, D. G. Hinks, and E. Bucher. Low-temperature order in the heavy fermion compound $CeCu_6$. *Phys. Rev. B* 52:R15 707-710.