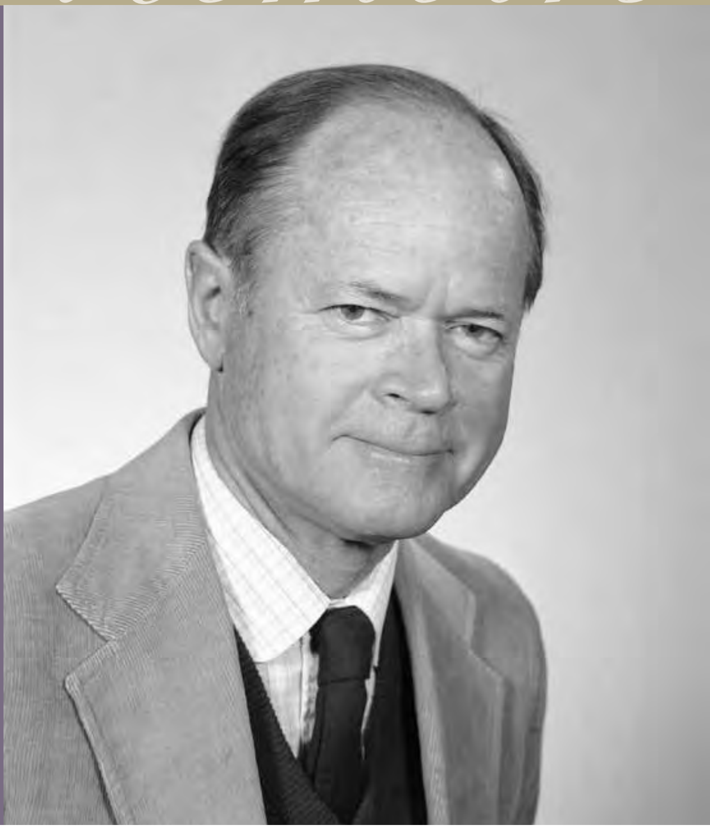
John C. Wheatley

1927–1986

BIOGRAPHICAL *Memoirs*



A Biographical Memoir by
Robert E. Ecke,
Gregory W. Swift,
and Oscar E. Vilches

NATIONAL ACADEMY OF SCIENCES

JOHN CHARLES **WHEATLEY**

February 17, 1927–March 10, 1986

Elected to the NAS, 1975

By Robert E. Ecke, Gregory W. Swift, and Oscar E. Vilches

John Wheatley was one of the preeminent physicists of his generation, best known for fundamental and original measurements that led to great advances in the understanding of quantum fluids and solids. During the 1950s, '60s, and '70s—with students, postdoctoral fellows, visitors, and colleagues at the University of Illinois at Urbana-Champaign, the Instituto de Física in Bariloche, Argentina, and the University of California at San Diego—John performed many of the pioneering experiments in normal liquid ^{3}He, in dilute solutions of ^{3}He in liquid ^{4}He, in solid ^{3}He, and in superfluid ^{3}He.

In normal ^{3}He and in the solutions, John's measurements sharply illuminated the roles of Fermi-Dirac statistics and interatomic interactions, thereby confirming new developments in Landau-Fermi liquid theory and breaking new ground in these nonmetallic Fermi fluids. In superfluid ^{3}He, John's measurements were among the first to illuminate the interesting similarities and differences between this superfluid and superconducting metals.

Throughout these decades, John believed in and practiced a coordinated synthesis of scientific research and technological development at ever lower temperatures. The advances in scientific understanding formed the foundation for new methods of refrigeration, thermometry, and measurement techniques, while the technological innovations enabled yet further advances in scientific experimentation.

For his many accomplishments, John received the two most prestigious awards in low-temperature physics: the Simon Memorial Prize (1965) and the Fritz London Award (1975). Elected to membership in the U.S. National Academy of Sciences in 1975, he was also a Sloan fellow and a Guggenheim fellow, twice had Fulbright fellowships, and was an elected fellow of the American Physical Society, American Academy of Arts and

Sciences, and Acoustical Society of America. John was especially proud of his honorary doctorate from The Netherlands' University of Leiden (1975)—on the occasion of the 400th anniversary of the founding of the university where helium was first liquefied and superconductivity was discovered—and of his being the only non-Finnish natural-sciences academician of the Academy of Finland (1980).

The science of ^{3}He

Terrestrial helium is almost all ^{4}He; useful quantities of the element's other stable isotope, ^{3}He, only became available around 1950 as an unintended byproduct of nuclear-weapons development. These helium isotopes condense into liquids at a few kelvin (the exact values depending on pressure), and below 25 atmospheres of pressure these liquids never freeze, even at the absolute zero of temperature, which makes helium unique among the elements. It automatically forms a pure liquid because impurities freeze and sink in it at these temperatures. A large quantum zero-point motion and a weak attraction between atoms cause its almost gas-like behavior. Quantum statistics govern helium's low-temperature properties: Bose-Einstein statistics for ^{4}He and Fermi-Dirac statistics for ^{3}He. (In electrons, the same Fermi-Dirac statistics manifest themselves via the Pauli exclusion principle, which leads to the electron-shell structure of atoms and the periodic table.)

The signature properties of a classical ideal gas, well approximated by air or helium gas at low pressures and room temperature, include pressure proportional to temperature and heat capacity independent of temperature. By contrast, a Fermi-Dirac gas at low-enough temperatures has its own power-law temperature characteristics; they include heat capacity proportional to temperature, viscosity inversely proportional to the square of temperature, and magnetic susceptibility independent of temperature, among other properties. John accurately confirmed many of these power-law dependences for liquid ^{3}He down to two to three millikelvin, with an accuracy that went beyond merely demonstrating the underlying Fermi-Dirac statistics—his measurements supported the quantitative development of Landau-Fermi liquid theory in which the character of the interactions between the fermions could be derived from these measured properties.

Perhaps the most beautiful check of Landau's theory was John's measurement of the propagation speed and the attenuation coefficient of sound in liquid ^{3}He. This experiment confirmed the existence of a novel oscillation-propagation mode called "zero sound," which does not exist in classical physics; it corresponds roughly to the propagation of a wave with wavelength much smaller than the atomic mean free path and with period much shorter than the interatomic collision time.

Dilute solutions of ^{3}He in liquid ^{4}He provide a more ideal realization of a weakly interacting Fermi gas than does pure ^{3}He. At temperatures below 100 millikelvin, the ^{4}He properties have essentially no temperature dependences, so the mixture can be regarded as a fluid of ^{3}He alone but whose number density is lower than that of pure liquid ^{3}He. John's careful measurements of the solutions' properties led to the first attempts at a microscopic theory of quantum mixtures by University of Illinois colleagues.

The superfluidity in ^{4}He below 2 kelvin, discovered in the 1920s, is characteristic of Bose-Einstein condensation. A lower-temperature transition to superfluidity in ^{3}He was anticipated, analogous to the superconducting transition in metals, because metallic electrons are also governed by Fermi-Dirac statistics. But theoretical predictions of the transition temperature varied by orders of magnitude. Following the discovery of ^{3}He superfluidity by Douglas Osheroff, Robert Richardson, and David Lee, John rapidly mapped out the superfluid phase diagram (including its pressure, temperature, and magnetic-field dependences) and made measurements of superfluid density, sound velocity and attenuation, heat flow, and magnetic susceptibility. Like the "Cooper pairs" of electrons in superconductors, superfluid ^{3}He depends on pairing of ^{3}He atoms. In both cases, the paired entities are fermions modified by strong interactions with their neighbors. The ^{3}He pairs, however, have nonzero angular momentum, so under certain conditions superfluid ^{3}He resembles a liquid crystal as well as a superconductor.

These quantum liquids—pure ^{3}He as well as ^{3}He–^{4}He solutions—are inherently fascinating while also illuminating related important phenomena in neutron stars and in the conduction electrons in metals.

Low-temperature technology

The evaporation of liquid helium absorbs heat and produces cooling, much like the evaporation of rubbing alcohol cools one's hands. As the vapor pressures of the helium isotopes decrease with decreasing temperature, however, the practical limit of evaporative cooling is about 1 kelvin for ^{4}He and 300 millikelvin for ^{3}He. To reach lower temperatures, other physical principles must be employed.

In adiabatic demagnetization refrigeration, a magnetic solid is magnetized by a solenoid and is initially precooled as far as possible by helium evaporation or other means. The solid is then isolated, and the solenoid's current is slowly reduced. As the magnetic spins in the solid become less constrained by the solenoid's magnetic field, they absorb heat from their own lattice and anything attached to it, thereby reducing the temperature. In his earliest developments in refrigeration, John advanced the technique of demagnetization of paramagnetic salts for cooling to a few millikelvin.

The endothermic mixing of liquid ^{3}He and ^{4}He offers another means of cooling, called ^{3}He–^{4}He dilution refrigeration. The technique had been used by British and Russian scientists to maintain temperatures below 100 millikelvin. John built and developed the first practical dilution refrigerator in the United States. It operated at around 10 millikelvin, using room-temperature pumps to circulate ^{3}He through a series of carefully engineered heat exchangers that precooled it step by step to near 10 millikelvin, dissolved it into the ^{4}He at that temperature, returned it through the heat exchangers, and distilled it from the ^{4}He at about 700 millikelvin en route back to the pumps. The dilution refrigerator revolutionized low-temperature physics by providing steady millikelvin temperatures for weeks or months at a time. It was a tremendous advance over demagnetization refrigerators, which require a carefully controlled decrease of solenoid current to maintain constant temperature for even a short time, and whose time-dependent magnetic fields can interfere with nearby magnetic thermometry or experimental measurements.

John's various labs followed a standard division of labor, with the most experienced students, postdocs, and visitors working on current science experiments, and the newcomers working on technological improvements or other relevant topics for the next generation of experiments.

Below about 100 millikelvin, the entropy of solid ^{3}He is higher than that of liquid ^{3}He, providing another opportunity for refrigeration—Pomeranchuk cooling (after Russian physicist Isaak Pomeranchuk)—in which pressurization of an equilibrium mixture of solid and liquid ^{3}He produces the cooling. John's clever design of a mechanical and hydraulic Pomeranchuk cooler produced what was at that time the lowest temperature for ^{3}He solid–liquid coexistence: 2 millikelvin.

Low-temperature ^{3}He physics also demands accurate measurement of the temperature dependences of various properties of ^{3}He—measurements that may further require accurate measurement of small temperature differences. Many of the innovations for accurate thermometry below 1 kelvin were invented or optimized by John. Among these innovations were powdered cerium magnesium nitrate (CMN) thermometry down to the millikelvin range, and the application of radio-frequency superconducting quantum interference devices (SQUIDs) to Johnson-noise thermometry and for reading out the feeble magnetic susceptibility of CMN thermometry.

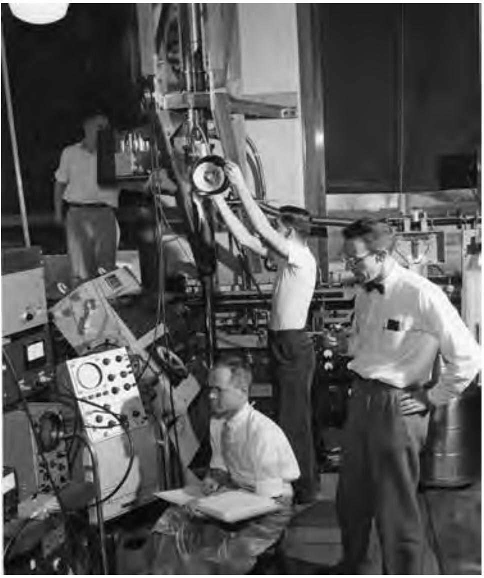
Scientist, adventurer, innovator

John was born in Tucson, Arizona, in 1927, the son of a Lutheran minister. He received his undergraduate degree in electrical engineering from the University of Colorado, Boulder, in 1947 and then went on to graduate study in physics at at the University of Pittsburgh. He met Martha Raup in the physics building there; she worked in the biophysics lab. They married in 1949 and would have three children: Bill (born in 1955), Ben (1956), and Jane (1959). John received his Ph.D. in physics from "Pitt" in 1952, under David Halliday.

John and Martha then moved to the University of Illinois at Urbana-Champaign, where he was an instructor—a non-tenure-track position. His dissertation research at Pitt and early investigations at Illinois involved the magnetic alignment of radioactive cobalt nuclei and the use of such nuclei for thermometry at low temperatures. He quickly became one of the promising young stars at Illinois, but in 1954 he resigned his position to accept a Guggenheim fellowship and a Fulbright research fellowship, a situation lamented by his departmental colleagues for fear he would not return. John used the fellowships to work for one year at the Kamerlingh Onnes Low Temperature Laboratory in Leiden and, for a short time, at Oxford University. The Leiden experience had a profound effect on him, steering his interests toward liquid ^{3}He research and giving him a lifelong appreciation of the importance of well-trained, specialized, and dedicated technical support.

At the end of his trip abroad, John was rehired at Illinois, this time as a tenure-track assistant professor, and there he started the vigorous low-temperature research program for which he became famous. As soon as ^{3}He became available in macroscopic quantities in the 1950s, the race was on to discover its superfluidity. John joined this race in earnest, systematically mapping out the properties of liquid ^{3}He and dilute solutions of ^{3}He in ^{4}He at ever-lower temperatures along the way, while simultaneously developing the refrigeration and thermometry technologies to do so.

John's various labs followed a standard division of labor, with the most experienced students, postdocs, and visitors working on current science experiments, and the newcomers working on technological improvements or other relevant topics for the next generation of experiments. For example, crystals and powders of cerium magnesium nitrate (CMN), a paramagnetic material, were used as thermometers and as adiabatic-demagnetization refrigerants in the millikelvin range. In addition to documenting the properties of this material, John measured the thermal conductivity and magnetic suscep-

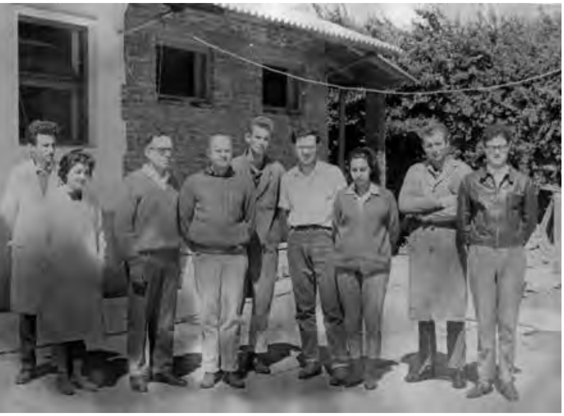


April 1957, Wheatley, seated, with Dillon E. Mapother (standing, right), Thomas Estle (standing, center), and Howard Hart (rear). (From Illinois Alumni News Vol 36, #3. Photo by Gliessman Studios, University of Illinois Alumni Association Archives, courtesy AIP Emilio Segre Visual Archives.)

tibility of structural materials (the good conductors of heat and the good insulators alike), invented new cell geometries to lower the thermal resistance between liquid ^{3}He and solids, and developed sealing techniques with epoxy suitable for use at millikelvin temperatures. Today, books on properties of materials at low temperatures are full of John's data.

For his second Fulbright Fellowship, beginning in 1961, John and his family went to San Carlos de Bariloche, Argentina, which lies in a national park in Patagonia near the border with Chile, among lakes, mountains, and volcanoes. The low-temperature laboratory at the Instituto de Física (now the Balseiro Institute) of the Centro Atómico Bariloche had been started only two years earlier. Immediately after arrival in Bariloche, John took complete command, providing the scientific and technological oversight and training that would lead to success at the lab. He reviewed everything being done and made substantial changes—including the dismantling of the hydrogen liquefier and of all the plumbing for the helium cryostat, and reassembling them to his extremely high standards. He assigned responsibilities to all of the lab's staff members, determined new thesis projects for the students, secured an instrument shop exclusively for the lab, helped upgrade the shop so that thermometry instruments could be built in-house, and added an extra person to the glass shop to help fabricate vacuum equipment and dewars. He had amateur radio sets installed in the physics departments in Urbana and in Bariloche so that he could keep track of progress in his Illinois lab and request supplies and spare parts to be purchased in the United States and sent to Bariloche. He also learned Spanish.

John not only led the building of the Bariloche lab, but he taught everyone what it took to be competitive worldwide at a time when there was little experimental physics



Bariloche group 1964. From left to right, Francisco de la Cruz, Maria Elena Porta de la Cruz, Ricardo Platzeck, John Wheatley, Claudio von Lucken, Oscar Vilches, Ana Celia Mota, Heriberto Tutzauer, Jose Cotignola.

in Argentina. His work ethic throughout was strict and friendly at the same time, though cultural differences and John's drive led to occasional misunderstandings and friction with some of the Argentinian staff and researchers. In the end, however, all was resolved amicably, and he was one of the strongest supporters of his Bariloche students for the rest of his life.

Although his family returned to Illinois at the start of the 1962–63 school year, John extended his stay in Bariloche another six months. By the time he left, liquid air, hydrogen, and helium had been produced there, adiabatic demagnetization refrigeration had been accomplished, and one research project was under way. He returned once more in 1964 to help fine-tune that experiment and initiate others, including a measurement of the heat capacity of pure ^{3}He down to millikelvin temperatures (which constituted the first complete experimental Ph.D. thesis done in the Bariloche low-temperature laboratory). Under the subsequent leadership of students that John helped train, the laboratory became one of the premier experimental research centers in South America. John's efforts on behalf of the Bariloche laboratory have been recognized by the American Physical Society's establishment of the biennial John Wheatley Award "to honor and recognize the dedication of physicists who have made contributions to the development of physics in countries of the third world."

Back in Illinois, John supervised all aspects of the lab work, arriving early and leaving late. On Saturday mornings, colleague John Bardeen visited to hear results from the week and contribute theoretical ideas. On Saturday afternoons, John (Wheatley) headed home to St. Joseph, where he and Martha had a home on a large lot with a creek running through it. In the summer he biked to and from work, and in the winter he organized ice-skating parties on nearby frozen ponds. Most summers the lab shut down for two to three weeks for vacation. Once, John took the whole family on a six-week adventure, driving from Urbana to Alaska in a four-wheel-drive sport-utility vehicle and camping along the way.

By the mid-1960s, John had completed measurements of the temperature dependences of ^{3}He's heat capacity, thermal conductivity, magnetic susceptibility, expansion coefficient, and self-diffusion (i.e., mass-diffusion) coefficient. Many of these measurements were made at elevated pressure in addition to low pressure, and many were made in dilute solutions as well as in the pure liquid. The speed and attenuation of zero sound had been measured, too—a remarkable phenomenon that exists only in a Fermi liquid and was predicted by Lev Landau before anyone had observed it.

In 1966, John learned about early developments in ^{3}He–^{4}He dilution refrigeration at a conference in England. Being a formidable thermodynamicist and engineer, he sketched a design for a new type of dilution refrigerator during the airplane flight home. This machine would use several discrete heat exchangers (as opposed to the continuous counter-flow heat exchanger used in England), and he predicted that its operating temperature would be 10 millikelvin. In 50 days, John's first dilution refrigerator was built and tested, achieving a bottom temperature of 20 millikelvin, close to John's predictions. But its performance deteriorated as it ran, and small modifications proved ineffective in solving this problem, so John decided to carefully study each component of the refrigerator to sort things out. This approach succeeded. John subsequently wrote two extensive articles on the construction and testing of practical dilution refrigerators, and many refrigerators were built in the United States and elsewhere following these articles and John's freely given advice. His basic dilution-refrigerator design is the one presented in classic books on cryogenic techniques.

In late 1966, John began a transition to the University of California at San Diego (UCSD), where he would have much more space than at Illinois, a dedicated machine shop, and a technician specializing in low-temperature equipment. From this base, John planned an all-out effort to search for superfluidity in ^{3}He, which would require a new and large dilution refrigerator to be used merely as a precooler for an even colder refrigerator. By the middle of 1968 his machine shop and technician were in place and the large dilution refrigerator was under construction; the first experiments were run in early 1969. Two other projects, on SQUIDs and Pomeranchuk refrigeration, were also started.

With world-class millikelvin refrigeration and thermometry, John's UCSD lab was the most exciting place imaginable to be a low-temperature physicist. John developed the Pomeranchuk effect into a practical cooling technique, precooled by the large dilution refrigerator, and in 1969 published ^{3}He measurements down to 2 millikelvin. It is quite likely that his Pomeranchuk refrigerator had superfluid ^{3}He a little before anyone else's, but its subtle signature was not noticed at that time. In the early 1970s—after the discovery of the ^{3}He superfluid transition by Osheroff, Lee, and Richardson and after Anthony Leggett's insightful interpretation of the new superfluid—John quickly built a new cryostat that used a dilution refrigerator to precool a copper nuclear demagnetization refrigerator. The first experimental run produced some 10 publications on various properties of superfluid ^{3}He, half of them in *Physical Review Letters*. In 1975, Leggett and Wheatley published independent, comprehensive, complementary reviews of theoretical and experimental work on the new superfluid in the *Reviews of Modern Physics*, only three years after its discovery.

University of California, San Diego physics faculty circa 1969. Wheatley is fourth from left in the front row. (Photograph courtesy University of California, San Diego.)

It was at this time that John and some colleagues and former students started the SHE Corporation (for superconductivity, helium, and electronics), located not far from the UCSD campus. Their initial product was a dilution refrigerator, in several sizes and configurations, which sold quite well around the world for many years. The second line of products was based on SQUIDs, which eventually became the main SHE product line (and led decades later to the production of magnetoencephelography equipment for medical diagnoses). John divided his time between the monumental UCSD low-temperature research effort and the demands of this high-tech start-up company, for which he was the on-site de-facto CEO and CTO.

In the late 1970s, John's professional interests grew beyond the fundamentals of ^{3}He and the technology needed to study it. At UCSD he began research on thermodynamic cycles of single-component supercritical fluids and on the basics of Rayleigh-Bénard convection. At about the same time, he planned his move from UCSD to Los Alamos National Laboratory, which held several attractions for him. The many applied-energy projects in its Low Temperature Group concretely demonstrated to John the Los Alamos commitment to technology development in parallel with basic research, and they also hinted at what would soon grow to be significant institutional support of commercial spinoffs. Also, the strong cadre of skilled technicians at Los Alamos fit the mold that John had appreciated ever since his days in Leiden. In the winter of 1980–81, he moved to Los Alamos, occupying thousands of square feet of lab space, fabrication/assembly/technical-support space, and plenty of office space.

Work was soon under way in supercritical-fluid engines and refrigerators (both at cryogenic and near-ambient temperatures), in "natural" engines and refrigerators (i.e., standing-wave thermoacoustics), in sub-kelvin Rayleigh-Bénard convection, and in spin-polarized hydrogen. Later, experiments on superfluid ^{3}He and localized states in nonlinear classical-physical systems were added. Participants, all under John's guidance, included UCSD graduate students, long-term visitors, postdocs, Los Alamos staff members, and three full-time technicians supporting the entire team.

John Wheatley, approximately 1982.

At Los Alamos, John continued his 60-hour-per-week work habit, interrupted only by Sunday hiking, skiing, or biking with Martha, and only partially interrupted by an annual month "off" at their cliff-top cabin on the west shore of Lopez Island (in the state of Washington), where they biked and kayaked and he also caught up on his writing. He rode his bike to and from work on all but the most intensely cold or snowy winter days in Los Alamos, reflecting both his genuine enjoyment of biking and a practical response to a family history of heart disease. John often wore shorts to work, ready to hop on the bike for lunch on a sunny rock a mile away if time allowed and the weather was good. After cardiac bypass surgery in the summer of 1983, he was back on his bike quickly.

At an age and level of accomplishment when many scientists shift from research toward other forms of public service, John continued to focus directly on science and technology. He always had one experiment of his own to do, and nothing at work gave him more pleasure than mixing his own epoxy, handling his own wrenches, taking and plotting his own data, and interpreting his own measurements.

He also enjoyed coaching and guiding the members of his large team, staying involved with every experiment so as to understand and contribute to important aspects of the work, and experiencing real delight at every new discovery and innovation, large or small. His passion for excellence was contagious.

As the original set of graduate students who had moved with him from UCSD to Los Alamos finished their work, he realized that a new arrangement would be necessary to recruit future generations of capable students to his Los Alamos team. He also missed classroom teaching; his time at Los Alamos made him realize how much he was still a physics professor at heart. A solution was readily at hand, however: because the University of California managed Los Alamos National Laboratory in those days, it was easy to team up with a UC campus. In 1985, John began what he intended to be alternating six-month periods at UCLA and Los Alamos. But near the end of the first six months in Los Angeles, John's heart stopped during one of his daily bicycle commutes, tragically ending his life at the age of 59.

John Wheatley was a brilliant, energetic, and dedicated scientist and technological innovator. He had a memorable impact on everyone who worked with him from the 1950s through the 1980s. From decades of focused experience coupled with great inherent intelligence, John had developed remarkable insights into physical phenomena and an outstanding ability to explain experimental data or direct new courses of action in the pursuit of an experimental goal. In the areas of his expertise, John was seldom wrong, as his many students, postdocs, and other colleagues rapidly discovered. He demanded perfection of himself, and he pushed for perfection in others.

The pressure that John's colleagues felt wasn't personal or unfair—it was simply objective and honest, driven by a desire to clarify and advance the science or technology under consideration. He expected those around him to be dedicated, generous, cheerful, and sharp, day after day, as he himself was. We remember John as a larger-than-life figure with a passion for science, a love of thermodynamics and fluid mechanics in particular, and an adventurous spirit—as happy on a cross-country motorcycle trip or on his daily bicycle commute as he was in the exotic world of low-temperature physics.

In writing this memoir, we have drawn on "John Wheatley (1927–1986): Pushing the Limits," a roundtable discussion published in *Los Alamos Science*, Number 14, Fall 1986; on a transcript of the John C. Wheatley Memorial held at the UCLA physics department on April 5, 1986; and on our own memories as three of his many students and postdocs. We are grateful to Maria Elena de la Cruz, Ana Celia Mota, and Raul Rapp for their comments on working with John in Bariloche and at UCSD, and to Martha, Bill, and Ben Wheatley for personal details about him.

For readability of this memoir, we have abbreviated "John and his young colleagues" or "John's group" to simply "John" in over a dozen places, expecting readers to know that accomplishments like his depend on the hard work and creativity of many students, postdocs, visitors, and colleagues too. Their contributions were essential, and the record of John's publications shows who they are.

SELECTED BIBLIOGRAPHY

1960 With H. R. Hart, Jr. Self-diffusion in liquid ^{3}He. *Phys. Rev. Lett*. 4:3–5.

1961 With A. C. Anderson, G. L. Salinger, and W. A. Steyert. Specific heat and thermal boundary resistance of liquid ^{3}He. *Phys. Rev. Lett*. 6:331–334.

With W. R. Abel, and A. C. Anderson. Propagation of sound in ^{3}He. *Phys. Rev. Lett*. 7:299–301.

1962 With A. C. Anderson and W. Reese. Magnetic properties of ^{3}He at low temperatures. *Phys. Rev*. 127:671–681.

1963 With A. C. Anderson and W. Reese. Specific heat, entropy, and expansion coefficient of liquid ^{3}He. *Phys. Rev.* 130:495–501.

1965 With W. R. Abel, A. C. Anderson, and W. C. Black. Thermal and magnetic properties of liquid ^{3}He at low pressure and at very low temperatures. *Physics* 1:337–387.

1966 With W. R. Abel and A. C. Anderson. Propagation of zero sound in liquid ^{3}He at low temperatures. *Phys. Rev. Lett*. 17:74–78.

With A. C. Anderson, W. R. Roach, and R. E. Sarwinski. Heat capacity of dilute solutions of liquid ^{3}He in ^{4}He at low temperatures. *Phys. Rev. Lett*. 16:263–264.

With A. C. Anderson, D. O. Edwards, W. R. Roach, and R. E. Sarwinski. Thermal and magnetic properties of dilute solutions of ^{3}He in ^{4}He at low temperatures. *Phys. Rev. Lett*. 17:367–372.

1967 With W. R. Abel, R. T. Johnson, and W. Zimmerman, Jr. Thermal conductivity of pure ^{3}He and of dilute solutions of ^{3}He in ^{4}He at low temperatures. *Phys. Rev. Lett*. 18:737–740.

1968 Dilute solutions of ^{3}He in ^{4}He at low temperatures. *Am. J. Phys*. 36:181–210.

With O. E. Vilches and W. R. Abel. Principles and methods of dilution refrigeration. *Physics* 4:1–64.

1969 With R. T. Johnson, R. Rosenbaum, and O. G. Symko. Adiabatic compressional cooling of ^{3}He. *Phys. Rev. Lett.* 22:449–451.

With A. C. Mota, R. P. Platzeck, and R. Rapp. Experimental heat capacity of pure liquid ^{3}He. *Phys. Rev.* 177:266–271.

1971 With R. E. Rapp and R. T. Johnson. Principles and methods of dilution refrigeration II. *J. Low Temp. Phys*. 4:1–39.

With L. E. Delong and O. G. Symko. Continuously operating ^{4}He evaporation refrigerator. *Rev. Sci. Instrum*. 42:147–150.

1972 With R. P. Giffard and R. A. Webb. Principles and methods of low-frequency electric and magnetic measurements using an rf-biased point-contact superconducting device. *J. Low Temp. Phys*. 6:533–610.

1973 With D. N. Paulson and R. T. Johnson. Propagation of collisionless sound in normal and extraordinary phases of liquid ^{3}He below 3 millikelvin. *Phys. Rev. Lett.* 30:829–833.

With R. A. Webb, T. J. Greytak, and R. T. Johnson. Observation of a second-order phase transition and its associated P-T phase diagram in liquid ^{3}He. *Phys. Rev. Lett*. 30:210–213.

With R. A. Webb and R. P. Giffard. Noise thermometry at ultralow temperatures. *J. Low Temp. Phys*. 13:383–429.

With T. J. Greytak, R. T. Johnson, and D. N. Paulson. Heat flow in the extraordinary phases of liquid ^{3}He. *Phys. Rev. Lett.* 31:452–455.

1974 With H. Kojima and D. N. Paulson. Propagation of fourth sound in superfluid ^{3}He. *Phys. Rev. Lett*. 32:141–144.

With D. N. Paulson and H. Kojima. Profound effect of a magnetic field on the phase diagram of superfluid ^{3}He. *Phys. Rev. Lett*. 32:1098–1101.

1975 Experimental properties of superfluid ^{3}He. *Rev. Mod. Phys*. 47:415–470.

1979 With D. N. Paulson, M. Krusius, R. S. Safrata, M. Koláč, T. Těthal, K. Svec, and J. Matas. Magnetic thermometry to below one millikelvin with lanthanum-diluted cerium magnesium nitrate. *J. Low Temp. Phys*. 34:63–82.