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EDWIN MATTISON MCMILLAN

1907—1991

A Biographical Memoir by

J. DAVID JACKSON AND W.K.H. PANOFSKY

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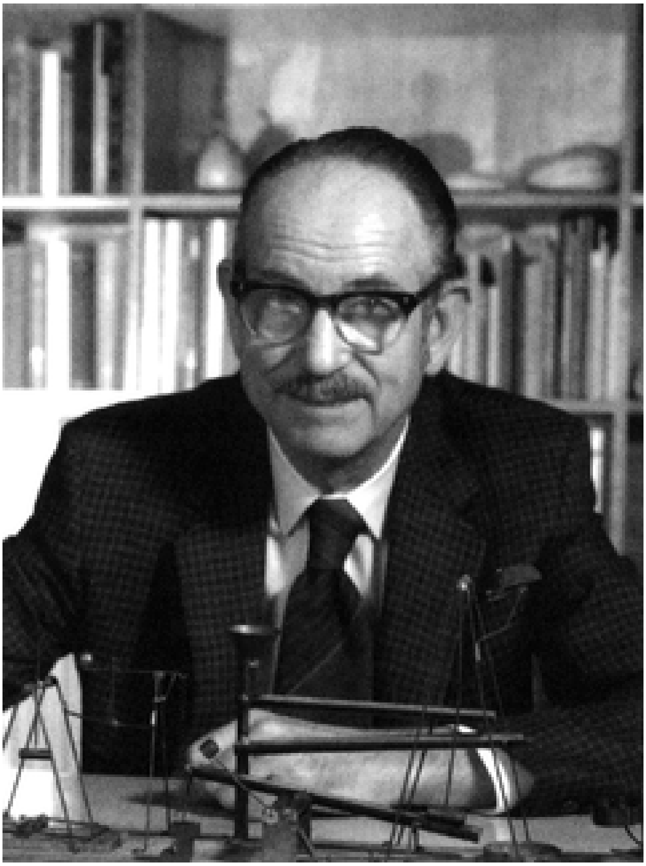

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EDWIN MATTISON MCMILLAN

September 18, 1907–September 8, 1991

BY J. DAVID JACKSON AND W. K. H. PANOFSKY

WITH THE DEATH OF Edwin Mattison McMillan on September 8, 1991, the world lost one of its great natural scientists. We advisedly use the term "natural scientist" since McMillan's interests transcended greatly that of his profession of physicist. They encompassed everything natural from rocks through elementary particles to pure mathematics and included an insatiable appetite for understanding everything from fundamental principles.

Edwin McMillan spent a large part of his professional life in close association with Ernest O. Lawrence[1] and succeeded Lawrence as director of what is now the Lawrence Berkeley Laboratory in 1958. Yet the two men could hardly be more different. Lawrence was a man of great intuition, outgoing, and a highly capable organizer of the work of many people. Edwin McMillan was thoroughly analytical in whatever he did and usually worked alone or with few associates. He disliked specialization and the division of physics divided into theory and experiment. He remarked at an international high-energy physics meeting, "Any experimentalist, unless proven a damn fool, should be given one half year to interpret his own experiment."

McMillan's first and last publications illustrate the unusual breadth of his interests. While still an undergraduate student in 1927, he published a paper[2] on the x-ray study of alloys of lead and thallium, clearly a topic in chemistry. At the time, he took many more courses in chemistry than was customary for a physics major, and this publication was undertaken at the suggestion of Linus Pauling. His last paper,[3] written together with the mathematician Richard P. Brent, was on an improved algorithm for computing Euler's constant: the limit of the difference between the sum of the inverse integers from 1 to n and the natural logarithm of n, as $n \rightarrow \infty$.

One of us (J.D.J.) recalls an incident that illustrates Ed McMillan's range in science. When Jackson corresponded at the beginning of 1957 with Luis Alvarez and his colleagues about muon-catalyzed fusion, he was startled to receive facsimile copies of handwritten notes by McMillan on a calculation of the mu-mesic molecular formation process! At that time, he knew McMillan's name as the discoverer of neptunium, the codiscoverer of plutonium, and the inventor of phase stability in accelerators but never dreamt that he was a molecular theorist! At the time, Ed was busy as associate director under Lawrence. His molecular physics Ph.D. thesis research with Condon could be the origin of such expertise, but with McMillan it could just as easily be knowledge acquired for the fun of it.

The son of Edwin H. McMillan and Anna Maria Mattison, Edwin M. McMillan was born on September 18, 1907, in Redondo Beach, California; both parents were Scots. He was brought up in Pasadena, California, beyond age one and a half. His father was a physician, as were the parents of his wife Elsie McMillan (born Blumer), who incidentally is the sister of E. O. Lawrence's wife, Molly. McMillan is survived by his wife and their three children (Ann Bradford Chaikin, David Mattison McMillan, and Stephen Walker McMillan). They were a wonderful and harmonious family.

As a child, McMillan built gadgets and made use of the proximity of the California Institute of Technology in attending lectures and seminars and getting acquainted with physicists there. After high school McMillan entered CalTech, where he had a first-rate academic record leading to both the B.S. and M.S. degrees. He completed his work leading to the Ph.D. at Princeton University in 1932.

McMillan's work can be separated into five phases that exhibit a great deal of overlap—not surprising considering the universality of McMillan's interests: (1) the early prewar period; (2) studies of the transuranic elements; (3) military work during World War II; (4) accelerator physics; and (5) laboratory director. These phases were paralleled by work on advisory committees and other roles as a statesman of science.

THE EARLY PREWAR PERIOD

McMillan's Ph.D. thesis, under Professor E. U. Condon, examined the generation of a molecular beam of hydrogen-chloride nuclei in a nonhomogeneous electric field.[4] In parallel, McMillan received a thorough education in experimental nuclear physics at Princeton. He published a paper[5] on the isotopic composition of lithium in the sun from spectroscopic observations immediately after receiving his Ph.D. He then won a highly prized National Research Council (NRC) fellowship, supporting him at any university of his choice.

He accepted the invitation of E. O. Lawrence to come to Berkeley, where Lawrence was at the time engaged in exploring the experimental potential of the cyclotron. After McMillan accepted Lawrence's invitation, he dedicated his first two years to activities somewhat separate from the mainstream activities of Lawrence's new Radiation Laboratory. He intended to measure the magnetic moment of the proton, but that plan came to naught when Otto Stern and collaborators in Germany did the measurement. He continued to work on hyperfine structure as revealed in optical spectroscopy and published papers on the nuclear magnetic moment of tantalum[6] as well as on the hyperfine structure of the solar spectrum.[7] But McMillan became progressively more involved with the work on Lawrence's cyclotron, which by early 1934 could produce a deflected beam of 2.3-MeV deuterons. His experimental skill was recognized by Lawrence and his collaborators and was put to increasing use on both the cyclotron and its instrumentation and physical experiments with the beam.

McMillan used the extracted deuteron beam in collaboration with M. Stanley Livingston to irradiate nitrogen to produce the positron emitting ^{15}O. Again, McMillan's skill as a chemist was put to work. He used a tracer technique in which first nitrogen gas was bombarded and then mixed with oxygen and an excess of hydrogen. This mixture was catalyzed to water over heated platinized asbestos, and the water was collected on anhydrous calcium chloride. The radioactivity was shown to be localized in the calcium chloride and absent elsewhere, proving that oxygen carried the activity.[8]

This work was followed by fundamental studies on the absorption of gamma rays,[9] which revealed the (at that time new) process of electromagnetic pair production in the Coulomb field of a nucleus. The 5.4-MeV gamma ray produced by bombardment of fluorine with protons and also the gamma rays of other isotopes were absorbed by foils of aluminum, copper, tin, and lead, enabling McMillan to isolate the components of the absorption process. At 5.4 MeV, electron-positron pair production is about one-half the total absorption cross-section in lead.

In 1935, with Lawrence and R. L. Thornton, McMillan studied the radioactivity produced when a variety of targets are exposed to a deuteron beam.[10] At deuteron energies below 2 MeV, the activity increases rapidly with energy, as expected from the quantum mechanical penetration of the Coulomb barrier, first used to explain alpha radioactivity lifetimes by George Gamow. The experiments of McMillan and coworkers on (d,p) reactions with energies up to 3.4 MeV showed that the yield curves flattened above 2 MeV, even though the Coulomb barrier effects were expected to be considerably steeper from conventional estimates of the effective nuclear radii. A deuteron seemed to be able to have its neutron captured by the target nucleus while its proton remained relatively far away. These data intrigued J. Robert Oppenheimer and his student, Melba Phillips, who then developed the theoretical explanation of the phenomenon: the small binding energy, and therefore large size, of the deuteron permits it to be polarized in the nuclear Coulomb field; this polarization places the neutron within the deuteron close to the nucleus, accessible for capture, while the proton is away from it. In essence, the proton becomes a "spectator" of the process. The Oppenheimer-Phillips process gives a quantitative explanation of the energy independence of the yield curves and the predominance of the (d,p) reactions in deuteron bombardments.

Following this work McMillan investigated the properties of ^{10}Be, with its extraordinarily long half-life for a light element (approximately 2.5 million years). He pursued further details of the properties of ^{10}Be in later publications.[11] During that period McMillan did several additional experiments in what today has become nuclear chemistry, some of them successful and some unsuccessful. At the same period, he wrote a seminal paper[12] on the production of X rays by the acceleration of very fast electrons, a subject in which he maintained a lifelong interest.

McMillan made numerous experimental contributions to the cyclotron, in particular to its beam-focusing properties, to beam extraction, and to vacuum gauges. His deep understanding of the factors that limit the energy attainable by conventional cyclotrons is illustrated by his correspondence in late 1937 and early 1938 with Hans Bethe. Bethe had worked with M. E. Rose at Cornell on the energy limit problem, and McMillan was carrying out calculations at Berkeley with Robert R. Wilson developing orbit-tracing methods. In 1937 Bethe sent an advance copy of the Bethe-Rose paper to McMillan. McMillan found some errors in the paper and showed that the electrostatic defocusing effect of the cyclotron dee's could be counteracted by the insertion of grids. McMillan also understood clearly the focusing effect of the radial fall-off of the magnetic field and the magnitude of the deviation from the synchronicity condition in the cyclotron produced by that radial fall-off, added to the relativistic mass increase. Bethe suggested that McMillan publish his findings, but characteristically McMillan felt that an additional paper would be redundant. The correspondence demonstrates McMillan's deep quantitative mastery of the subject while at the same time exhibiting his basic humility. He preferred making an input to the Bethe-Rose paper over cluttering up the literature with controversy.

STUDIES ON TRANSURANIC ELEMENTS

The discovery of fission of uranium by Hahn and Strassmann in 1939 initiated intense activity worldwide. At Berkeley McMillan first performed a simple experiment to measure the ranges of the energetic fission fragments by exposing a thin layer of uranium oxide on paper sandwiched between several thin aluminum foils on either side to the neutrons from 8-MeV deuterons striking a beryllium target in the 37-inch cyclotron. The amounts of radioactivity in successive foils established the maximum range of the fragments as equivalent to approximately 2.2 centimeters in air. He also used cigarette papers instead of the aluminum foils in another sandwich and followed the radioactivity in different papers after bombardment, finding the same time dependence in all. In contrast, the activity associated with the layer of paper on which the uranium oxide had been placed had different components. In addition to the fission fragment activity, there was one component with a twenty-five-minute half-life and another of roughly two days. McMillan speculated that the twenty-five-minute activity was ^{239}U, identified earlier by Hahn and co-workers as a product of resonant neutron capture in uranium.[13]

The two-day nonrecoiling activity intrigued McMillan. Accordingly, he bombarded thin ammonium uranate layers deposited on a bakelite substrate and covered with cellophane (to catch the energetic fission fragments). After exposure to the neutrons, the ammonium uranate was scraped off the bakelite and its activity followed. At long times the 2.3-day activity was dominant; at short times, the twenty-three-minute half-life of ^{239}U predominated. In contrast, the cellophane showed the characteristic power law decay associated with a mixture of fission fragments of different lifetimes. With the new activity physically separated, it was possible to begin study of its chemical properties. As a putative new element next to uranium, the activity seemed likely to have chemical properties akin to rhenium. McMillan therefore enlisted Emilio Segrè, who was familiar with the chemistry of rhenium from his discovery of a homolog, technetium, in 1937. Segrè found that the 2.3-day activity behaved like a rare earth, not like rhenium. Since rare earths are prominent among the fission fragments, it appeared that the 2.3-day activity was one of those. After a gap in his pursuit, McMillan had become persuaded by early 1940 that the nonrecoiling 2.3-day activity just could not be the decay of a fission fragment. He began a set of experiments with the new 60-inch cyclotron and its 16-MeV deuterons. Two observations confirmed his belief as a certainty. One, using cadmium absorbers to reduce the thermal neutrons, showed greatly reduced fission activity but left the two nonrecoiling activities in the same relative proportion. The other, a fission product experiment with extremely thin collodion catcher foils, showed that the range of the 2.3-day "fragments" was less than 0.1 millimeter of air equivalent. The 2.3-day activity could not be from fission; the twenty-three-minute and 2.3-day activities almost certainly were genetically related. The beta decay of ^{239}U was producing atoms of a new element with $Z = 93$! McMillan found chemically that the 2.3-day activity had some, but not all, the characteristics of a rare earth.

Philip H. Abelson was a student at Berkeley in 1939, working on the chemistry of fission products and was familiar with McMillan's first observations of the 2.3-day activity. In 1939-40 at the Carnegie Institution in Washington, D.C., Abelson attempted (unknown to McMillan) to separate the 2.3-day activity, initially with rare-earth chemistry, but found his procedures inadequate. In May 1940, as McMillan was doing his chemistry, Abelson came to Berkeley and they began a collaboration. The key to successful chemistry, as Abelson found, was control of the state of oxidation of the material. In the reduced state the activity coprecipitates with rare-earth fluorides; when in an oxidized state it does not. In fact, the oxidized state behaves similarly to uranium, coprecipitating with sodium uranyl acetate. On the other hand, uranium does not precipitate in an HF solution with SO_2, while the 2.3-day activity coprecipitates with rare-earth carriers. Abelson and McMillan were thus able to use an "oxidation-reduction cycle" to make a series of precipitations of the 2.3-day activity from a uranyl solution and establish its growth from the twenty-three-minute ^{239}U, thus proving it to be an isotope of element 93. They searched for alpha activity associated with the decay product of the 2.3-day isotope (an isotope of element 94) and noted that it must be long-lived. The work was submitted to the *Physical Review* on May 27, 1940.[14] The technique of an oxidation-reduction cycle formed the basis of all the transuranic chemistry to follow.

After Abelson's return to Washington, McMillan turned to the search for the alpha activity of the daughter of ^{239}Np (as we now denote it). Strong samples of the 2.3-day activity did show some alpha particle emission, distinguished from possible natural uranium activity by greater range. With the hope of producing a different isotope of neptunium and so its decay product, McMillan bombarded a uranium target directly with 16-MeV deuterons. A two-day beta activity, with more energetic beta particles than the earlier 2.3-day decay, was observed, along with a considerably more intense 5-MeV alpha activity (now known to be from ^{238}Pu; ninety-two-year half-life). He tried to separate the alpha activity chemically, eliminating protactinium, uranium, and neptunium as species, while showing that it behaved similarly to thorium and 4-valent uranium.

In November 1940 McMillan left Berkeley for military work at MIT. Glenn T. Seaborg, who, with colleague J. W. Kennedy and graduate student A. C. Wahl, had perfected the oxidation-reduction technique for isolating neptunium, wrote to McMillan to say that they would "be very glad to carry on in his absence as his collaborators" in the search for element 94.[15] McMillan replied (in Seaborg's words), "informing me that he will not be back soon in Berkeley and it would please him very much if I continue to work on elements 93 and 94."[16] McMillan's letter explicated his own findings on the physical and chemical characteristics of the various activities.

Following McMillan's lead, by late February 1941 Seaborg, Kennedy, and Wahl had made definite the discovery of the ninety-two-year isotope of element 94 (^{238}Pu). A short paper on the joint work with McMillan was submitted to the *Physical Review* on January 28, 1941 (before the final proof of separation from thorium had been made) but was voluntarily withheld from publication until 1946.[17]

For his discovery of neptunium with Abelson and of plutonium with Kennedy, Seaborg, and Wahl, McMillan shared with Seaborg the Nobel Prize in chemistry in 1951.

MILITARY WORK DURING WORLD WAR II

McMillan's first assignment at MIT in November 1940 was work on airborne microwave radar at the newly established MIT Radiation Laboratory. The work initially capitalized on his technical and physical ingenuity, but when emphasis shifted from individual invention to collaborative engineering, McMillan moved to the U.S. Navy Radar and Sound Laboratory in San Diego in 1941. There he invented and developed a repeater for underwater echoes that greatly extended the detection range of undersea warfare devices. He was then recruited by J. Robert Oppenheimer, who had been appointed director of the Los Alamos weapons laboratory to be and served as his principal adviser on practical technical issues, starting in the fall of 1942.

McMillan's nuclear weapons work started with the site selection of Los Alamos. He then led the development of the gun-type weapon, a device in which ^{235}U bodies are fired at one another with a gun to constitute a critical assembly. A requirement for such a device to work meant the development at a separate site near Los Alamos of gun barrels of lower weight to propel objects at higher speed than was previously considered feasible. The work then continued with McMillan serving as deputy to William S. (Deak) Parsons, the naval officer who was then in charge of all conventional explosive work at Los Alamos. McMillan's work proceeded until it was established that the gun device would work; he did not participate in the actual "weaponization." The Hiroshima weapon was based on these developments without a nuclear test. The rest is history.

Oppenheimer asked McMillan to undertake a large number of additional responsibilities. One was to serve as the liaison officer between Los Alamos and the California Institute of Technology project known as CAMEL, which among other activities tested the aerodynamic properties of air-dropped bombs, with McMillan in charge. Another experimental responsibility was development of diagnostics of the implosion assembly for the plutonium bomb, using a magnetic detector. McMillan was an observer during the Trinity Test when the first implosion device was detonated.

He and his wife Elsie were mainstays in the evolution of social life in Los Alamos with all its joys and heartbreaks.[18]

ACCELERATOR PHYSICS

By the middle of 1945 many scientists at Los Alamos, including McMillan, were making plans to return home. For the Berkeley physicists, this included planning new accelerator facilities. Before the beginning of the war Lawrence had started to construct a huge conventional cyclotron. It had a pole-face diameter of 184 inches and a magnet gap of 5 feet. McMillan had designed some power supplies for that machine. That large magnet gap was needed because the conventional cyclotron required dee voltages in excess of 1 million volts to reach energies close to 100 MeV. This voltage required very large clearances between the dee and the vacuum chamber walls. Acceleration had to be accomplished during very few turns in order to keep the particles in step with the accelerating rf voltage even with their relativistic increase in mass.

McMillan was fully acquainted with this situation, but he disliked pursuing the plan for completing the 184-inch cyclotron. In mulling over this problem, McMillan, in June 1945, envisioned the idea of phase stability, which in a single stroke of invention made this brute force approach obsolete. McMillan recognized that when particles are accelerated in a radiofrequency field not at the crest of the radiofrequency amplitude but on the side of the waveform, the particles would be locked stably at a certain phase. The idea had great generality and applied to many types of accelerators, including circular heavy particle and electron machines and heavy particle linear accelerators. For circular accelerators using magnetic fields uniform in azimuth, the phase stability region is during the *decreasing* part of the radiofrequency amplitude. If a particle has less than the normal energy, it is bent into a tighter circle in a circular accelerator and thus takes less time to complete its orbit. Such a particle thus arrives earlier at the next period and therefore is exposed to a higher accelerating field during the decreasing part of the rf amplitude. It therefore receives a larger energy increase. Conversely, a particle above average energy receives less acceleration. In consequence, the particles execute "phase oscillations" about a stable phase angle determined by the ratio of the peak acceleration made possible by the rf amplitude and the actual, lesser, acceleration required by the specific accelerator design.[19] McMillan expressed these facts in differential equations describing a stable "bucket" with particles oscillating about a synchronous phase within the bucket at a frequency defined by the accelerator parameters.

McMillan, in his discussions at Los Alamos, fully recognized the generality of this new principle and its wide range of application. He published[20] his discovery in the *Physical Review* in September 1945. After publication McMillan learned[21] that the Russian physicist Vladimir I. Veksler had conceived the same idea and had published it previously in a Russian journal that had not reached the United States during wartime. There followed an exchange of letters between Veksler and McMillan that will remain an example of gracious interaction between scientists. McMillan acknowledged[22] the priority in time of Veksler's invention. Both parties agreed that their respective inspirations were indeed independent and that the idea of phase stability would inevitably have surfaced.

In McMillan's words, "It seems to me that this is another case of a phenomenon that has occurred before in science—the nearly simultaneous appearance of an idea in several parts of the world, when the development of the science concerned has reached such a point that the idea is needed for its further progress." And in Veksler's words, "You are quite justified in saying that the history of science affords many examples of the simultaneous appearance of similar ideas in several parts of the world, as in our own case." The two physicists became friends and mutual admirers. They shared the Atoms for Peace Prize for the invention of phase stability in 1963.

The concept of phase stability revolutionized accelerator design and construction throughout the world. It led to proposals for new accelerators in France and at the new European laboratory at CERN, in the United Kingdom, and in Australia, and it led to vigorous initiatives in Russia and the United States.

The original plans for the "classical" 184-inch cyclotron were scrapped. The magnet was modified to produce a larger magnetic field over a smaller gap. This conversion made it into a "synchro-cyclotron." Here the principle of phase stability was used together with frequency modulation (provided by a rotating capacitor) of the rf accelerating field, needed to compensate for the relativistic change in orbital frequency. The ions, injected at the center of the synchrocyclotron magnet, are locked at stable phases in many orbits of increasing radius as they gain energy. Since synchronization is guaranteed by phase stability, acceleration can occur stably over many turns. Lower dee voltages are therefore sufficient, and a smaller gap and a higher magnetic field can be utilized.

A model was constructed in record time in the small 37-inch cyclotron on the Berkeley campus. The success of this model led to full-speed conversion of the 184-inch machine by 1948. That machine supported an impressive series of discoveries, including many important experiments on the first man-made pi-mesons. McMillan himself participated in the mapping of the neutron beam produced by high-energy deuterons on internal targets and was an advisory participant in innumerable experiments. However, his primary interest shifted to another application of phase stability, a 300-MeV electron synchrotron that became his responsibility for both construction and research supported by Lawrence and the Atomic Energy Commission.

Prior to the invention of phase stability, the highest energy reached by an electron accelerator was achieved with the betatron with its energy limit—about 100 MeV—set by that emission of electromagnetic radiation by the electrons.

In McMillan's machine the electrons were confined to an annular chamber and accelerated in the traditional betatron manner to about 2 MeV. Subsequent phase-stable gain in energy was produced by the electric field of an electromagnetic cavity as the guiding magnetic field is raised. McMillan's machine had a radius of 1 meter and attained an energy of 300 MeV. McMillan personally directed the building of all phases of this pioneering machine and contributed engineering ideas. There were technical problems with the vacuum chamber exposed to electromagnetic radiation; the magnets had to be designed for proper focusing and for control of eddy current effects; special power supplies involving high-current switching had to be built to control the time sequence of the magnets; the rf system had to be engineered.

Nevertheless, the job was done and the machine, like the 184-inch cyclotron, yielded important new discoveries. McMillan personally participated in the first experiments of production of pions by photons.[23] Many other experiments were done, including demonstration of the existence of the neutral pion and detailed studies of the high-energy electromagnetic cascades. The 300-MeV electron synchrotron gave McMillan, for the first time, the opportunity to direct all phases of an accelerator laboratory; he was designer and builder of the synchrotron and also manager of the scientific program associated with that novel tool, which could not have been built prior to the invention of phase stability.

The success of the 184-inch synchro-cyclotron and 300-MeV electron synchrotron provided the impetus for the next stage of accelerator building at Berkeley—the Bevatron. McMillan contributed to the initial concepts of the design of that machine, including the calculations that showed the machine should reach 6 GeV comfortably to produce proton-antiproton pairs. Construction was in the hands of William Brobeck, a highly capable engineer long associated with Lawrence and McMillan.

Today, essentially all high-energy accelerators, be they for electrons, protons, or heavy ions, could not operate unless they were "phase stable." The explosive development of high-energy accelerators, which led to an increase in obtainable energy by roughly a factor of ten per decade, is largely a consequence of the invention of McMillan and Veksler.

McMillan made other significant contributions to accelerator physics. He published[24] the "McMillan theorem," a mathematical proof that in a linear accelerator radial focusing and phase stability are mutually incompatible unless external focusing devices (magnet lenses or grids) are applied to the beam. He also carried out calculations on the spin motion in electron linear accelerators, and during a sabbatical visit to CERN in 1975 he traced the puzzling loss of muons in a storage ring to minute machining irregularities in the magnet pole faces. He contributed extensively to the analysis of orbit dynamics at the Berkeley laboratory.

LABORATORY DIRECTOR

While in the years after 1945 McMillan's research focused on the design and construction of accelerators at the Radiation Laboratory, his interest in other sciences remained acute. He was a faculty member in the Department of Physics, University of California at Berkeley, engaged in regular undergraduate and graduate teaching in the period 1946-54 and supervision of fifteen graduate students to the Ph.D. His classroom teaching ended with his appointment as associate director of the Radiation Laboratory (1954-58), becoming deputy director and, later that year after Lawrence's death in August 1958, director of the renamed Lawrence Radiation Laboratory.

McMillan served for fifteen years (1958-73) as director of the Lawrence Radiation Laboratory and, after separation of the Berkeley and Livermore components in 1970, the Lawrence Berkeley Laboratory (LBL). In 1958 the laboratory already had 2,000 employees in Berkeley and about

3,300 at Livermore. The Berkeley part was multidisciplinary, with the major focus on physics, with numerous accelerators, but also had divisions of nuclear chemistry, biology and medicine, and bioorganic chemistry. The vigorous particle physics research program at the Bevatron, with the 72-inch bubble chamber and a variety of electronic particle detectors, drew physicists from around the world and made the Berkeley laboratory the center of high-energy physics from the late 1950s to the mid-1960s. Work with the 184-inch cyclotron and McMillan's 300-MeV synchrotron remained active.

The first half of McMillan's tenure as director was perhaps the high point of LBL, at least in high-energy physics. The latter part of his term saw changes, both in the scientific effort at the laboratory and in its funding from Washington. By the early 1960s accelerators elsewhere achieved higher energies, and so the particle energy frontier began to move away from Berkeley. To McMillan higher-energy facilities were desirable and inevitable. In fact, he played an important role in the creation of Fermilab, serving on the board of the Universities Research Association in its formative years.

McMillan provided scientific and administrative leadership to the laboratory in increasingly complex times, with particle physics funding leveling off and Livermore beginning to dwarf Berkeley.[25] Maintaining a strong and diverse research program in physics and the other fields with limited resources was difficult. His tendency was to let the heads of the scientific divisions have free rein, but he did not hesitate to arbitrate conflicting views and set the laboratory's course when necessary. He was successful in maintaining a strong multidisciplinary laboratory, with growth in new fields such as energy conservation and the environment as older programs leveled off.

In the later years, the “Rad Lab” suffered internal and external stresses: internal, as some researchers disagreed on priorities among existing activities and clamored for scarce research dollars for alternative projects less firmly connected to the laboratory’s mission; external, as the partnership between the laboratory and the Atomic Energy Commission (ERDA after 1974) and the U.S. Congress began to erode. Moreover, the Vietnam war raised tensions, particularly on university campuses.

Lawrence had run the Radiation Laboratory from the beginning as a personal empire, and this benevolent stewardship from the top continued under McMillan, although he did not enjoy the exercise of power.

By the late 1960s, protesters against the Vietnam war and the military-industrial complex had tarred the Radiation Laboratory as a “bomb factory” and worse. The distinction between Livermore and Berkeley, while fully understood within the scientific community, was lost on the average person. The proximity of the Berkeley part of the Radiation Laboratory to the Berkeley campus made it an easy target for abuse. Within the laboratory tensions were rising, fueled by some faculty and graduate students who thought that the war was a legitimate topic for noontime discussion within the laboratory and members of the lab staff who did not. The issue hinged largely on conflicting views of the laboratory: a part of the academic campus, where free speech should prevail, or a governmental research enterprise, where politics was inappropriate.

Attempts to hold open meetings to discuss the Vietnam war were initially met with heavy-handed prohibition and discipline. Soon, however, McMillan saw that the protesters were sincere and responsible opponents of the war but not of the Berkeley Laboratory. In his quiet, cautious way, he addressed the perceived lack of academic freedoms at the laboratory. In the spring of 1971 he appointed an ad hoc committee of staff and faculty to draw up rules for independent open meetings at the laboratory. He promulgated these rules in September 1971, but the general counsel of the regents of the University of California promptly demanded that the rules be withdrawn. McMillan dug in his heels because he knew that the committee had transmitted all earlier drafts of its proposed rules to the general counsel for review. McMillan and the committee rejected most of the criticisms as trivial, made a few cosmetic changes, and left the rules in place to see them serve a useful purpose, without adverse consequences. McMillan did not like conflict, but he held strong principles. When he saw that something was fair and reasonable, he stuck to it over all objections.

Another example of McMillan's clear vision was the decision to separate Livermore from Berkeley. The turmoil in the country at large over the Vietnam war, the antimilitary sentiments, and the perceived security issues argued for separation. Voices at Livermore urged separation; voices at Berkeley urged the status quo—both for the same reason, money. The Livermore voices believed that the Berkeley side was riding the Livermore juggernaut; the Berkeley voices feared loss of support with separation. McMillan recommended separation and so became director of the smaller Lawrence Berkeley Laboratory. Funding did change, but not because of the separation and not for the worse. The subsequent profound changes in the Lawrence Berkeley Laboratory, with particle physics playing an ever-decreasing role, occurred under subsequent directors. McMillan stepped down as laboratory director at the end of 1973 and retired from the Berkeley faculty in June 1974. He continued to participate in the laboratory's work until he suffered a series of disabling strokes in 1984.

CONCLUSION

The above account of the five major phases of McMillan's contributions falls far short of describing his total contributions as a scholar, teacher, and human being. McMillan was an excellent teacher both inside and outside the classroom. His formal courses were extremely well received, with their clarity and total absence of preaching from on high. He instilled in his students an appreciation of physics in its fundamental aspects. He loved to explain scientific facts as well as gadgets to younger audiences, with his effectiveness resting entirely on deep knowledge combined with an absence of showmanship.

McMillan served on the then General Advisory Committee to the Atomic Energy Commission from 1954 to 1958 and participated as a member of scientific policy committees and program advisory committees to several laboratories. In committees McMillan tended to be relatively taciturn, but when he spoke up his remarks were decisive and to the point. When President Eisenhower in 1959 announced his decision to build the Stanford Linear Accelerator Center, he said, "I am told by the scientists that this is the most extraordinary thing that has been attempted . . ."; the spokesman referred to by the President was Ed McMillan.

McMillan's contributions to the progress of science did not go unappreciated. As mentioned above, he shared the Nobel Prize with Glenn Seaborg for his discoveries of transuranic elements, and he shared the Atoms for Peace Prize with Vladimir I. Veksler for the discovery of phase stability. He was elected to the National Academy of Sciences in 1947. He was awarded the National Medal of Science in 1990. Since by then he was confined to a wheelchair, the award was presented to his son, Stephen, by the President. McMillan received numerous other awards and honorary degrees, but none of this recognition affected his general humility. He did his work quietly, spoke concisely, and seemed to enjoy everything he was doing. He kept up with evolving knowledge in a surprisingly large number of fields.

In his private life McMillan was a good family man and was greatly supported in all he did by his wife Elsie. He liked hiking and exploring. His particular love was the Anza Borrego desert region, where he collected rocks and concretions that were spread around his office, house, and garden. He was interested in plants and grew orchids as well as insect-eating Venus Fly Traps.

In many of the obituaries Ed McMillan was flagged as an atomic bomb pioneer. Yet while the very discovery of plutonium and his subsequent work at Los Alamos were major contributions to the nuclear weapons program, his own views on nuclear weapons became increasingly critical after the war. He shunned all Cold War rhetoric and remained detached during the Korean War from efforts at Berkeley aimed at replenishing the plutonium supply when it appeared that the United States might be cut off from overseas supplies of uranium. The buildup of nuclear weapons during the Cold War led him to state publicly, "This country has in its hands some incredibly powerful weapons. The way our government deals with the question of nuclear disarmament is shameful—a disgrace to our nation."

Ed McMillan was a humble unassuming person. He enjoyed his science, all of nature, his friends, and his family. His great contributions seemed to flow naturally from him without apparent effort but as a simple product of his mind. The world is richer through Ed McMillan's contributions and poorer through his death.

NOTES

WE THANK EDWARD J. LOFGREN for opening his files on McMillan to us and Philip H. Abelson for a thoughtful perspective on McMillan's research in the prewar years.

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19. In a linear accelerator the situation is reversed. Here the stable phase angle exists at the *rising* part of the rf amplitude; a particle whose energy and therefore velocity are below the norm arrives late and therefore experiences a larger radiofrequency amplitude, with the converse being true for a particle whose energy and velocity are above the norm.
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25. By 1965 Livermore and its ancillary sites had 5,300 employees, and Berkeley had 3,200; the Livermore budget was two and a half times Berkeley's. McMillan was nominally director of the whole laboratory. When the Lawrence Berkeley Laboratory and the Lawrence Livermore Laboratory came into separate existences in 1970, Livermore was more than twice as large, with a budget more than three times that of Berkeley.

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