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VALENTINE LOUIS TELEGDI
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A Biographical Memoir by
LAURIE M. BROWN

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Biographical Memoir

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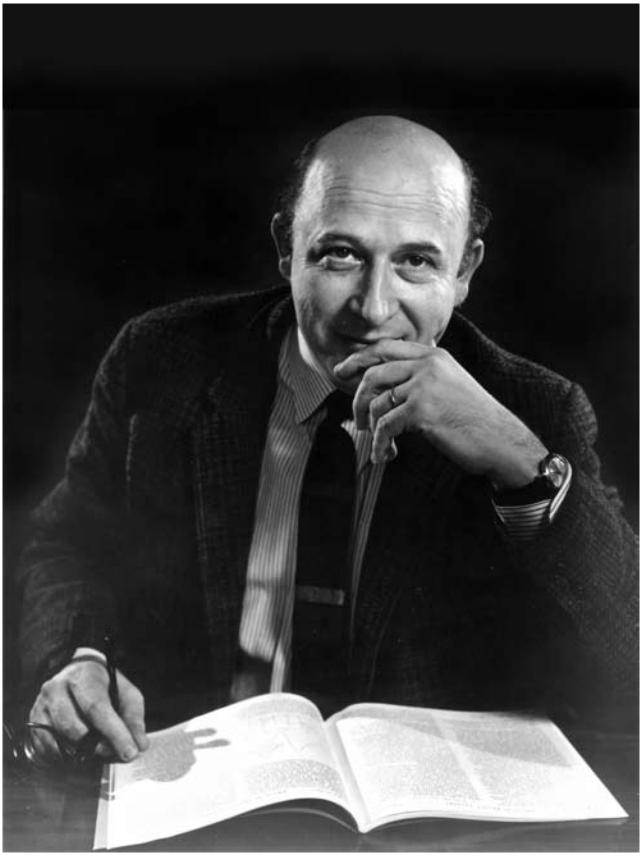

Valentine Louis Telegdi

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BY LAURIE M. BROWN

Valentine Telegdi was an outstandingly original experimental physicist who contributed greatly to our understanding of the weak and electromagnetic interactions of elementary particles. Outspoken and colorful in expression, Telegdi (usually called "Val") had the reputation of being a "conscience of physics," known for his incisive and sometimes acerbic wit. In this respect he was reminiscent of Wolfgang Pauli, one of his teachers, whom he greatly admired. However, Val could be warm and caring to friends, professional associates, and students. After receiving his doctorate from the Swiss Federal Institute of Technology (ETH) in Zürich in 1950, he began his academic career at the University of Chicago in 1951, and his reputation grew rapidly. In 1968 he was elected to the National Academy of Sciences. In 1972 the University of Chicago appointed him as the first Enrico Fermi Distinguished Service Professor of Physics.

In 1976 he left Chicago, returning to Switzerland, to hold a professorship at ETH and to work half-time at the European Center for Nuclear Research (CERN), where he headed an experimental group. Val and his wife, Lidia (née Leonardi, known as "Lia"), lived in Geneva, and he commuted weekly to ETH in Zürich, where he directed an atomic physics group and taught his classes. Beginning in 1981 Val and Lia spent part of each year in California, either at Caltech or at the University of California, San Diego.

Val's parents were Hungarian Jews.[1] His father, Georges, was born in Pécs, Hungary, near the Croatian border in 1897; his mother, Ella Csillag, was born in the same year in Békéscsaba, near Romania. In 1922 Val's father was working for a transportation company in Bulgaria, and his mother returned to her native Hungary to give birth to Val. Thus Val spent his earliest years in Bulgaria and in Romania until 1928, when the family returned to Budapest, where Val attended primary school. In 1932 they moved to Vienna, and Val attended high school (*Realgymnasium*) there until 1938. He soon became strongly attracted to chemistry and physics and began to read "serious science books" (Telegdi, 1987, p. 3).

Val's father had graduated from a commercial high school in Budapest in 1914. He greatly admired French culture and went to Paris when he received his diploma. After a few months the Great War started and he was detained as an enemy alien. On his return to Budapest five years later he found life in Hungary very difficult. It was the time of the Red Terror of Bela Kun, later put down by a White Terror, led by Admiral Horthy. So he looked for employment abroad and found work in Bulgaria. According to Val, his father was an accomplished linguist, "knowing (besides Hungarian) German, French, and English at a literary level. He later added Bulgarian, Rumanian, and modest Italian to these languages" (Telegdi, 1987, p. 2). Val himself had a similar talent, as Victor Weisskopf noted in 1987: "He speaks many possible and impossible languages (the latter are Hungarian and Schwytzerdütsch) practically without an accent. Strangely enough, he has a distinct accent in the language he uses most: English" (K. Winter, 1988, p. xxvi).

In Vienna at age 13 a birthday gift of a chemistry set strengthened Val's scientific interest, but after one of his experiments stained a dining table, he was forbidden to practice chemistry at home and started to read chemistry books at the National Library. Later he recalled, "It cost me no effort to become an obnoxious 'prodigy,' since I had a perfect memory . . . for assorted facts" (Telegdi, 1987, p. 3). Val spent his last two years in Vienna at a training school for laboratory technicians, the *Lehr-und Versuchsanstalt für chemische Industrie*. His parents moved to Italy, leaving Val to board in Vienna successively with two families. In 1938 while he was spending his school vacation with his parents in Milan, Germany annexed Austria (the *Anschluss*) and there was no question of his returning to Vienna.

In Italy Val continued his schooling in Bergamo at a similar vocational school, as his father thought that he was not suited to a university. He lived in a dormitory and concentrated on learning the Italian language, becoming fluent in a few months. Since it appeared that Italy was moving ever closer to Nazi Germany and war was threatening, Val's father wanted to send him to a technical college in Great Britain—to become "both a gentleman and a lab technician" (Telegdi, 1987, p. 6), However, that would have been too expensive, so in 1939 Val was enrolled in a vocational school in Brussels. When the Germans occupied Belgium a year later, Val having only a Hungarian passport, nevertheless managed to return to Italy with a group of Italians. They traveled through Nazi Germany in a sealed railway car, arriving on June 10, 1940, the day Italy entered the war. A few months later, Val's father moved to Lausanne, Switzerland, while Val and his mother remained in Milan.

Unable for various reasons to continue his studies in Italy, Val earned some money by doing technical translations. The head of a firm of patent attorneys, Dr. Farraggiana, took a liking to him, and finding him to have sufficient technical knowledge, gave Val a job working up foreign applications for Italian patents from Germany, Holland, England, and even the United States (during the war). Val wrote, "I did this patent work for three years. . . Those years were *extremely important* for my scientific development. . . I learned . . . there how to find the essential points in a maze of almost irrelevant information" (Telegdi, 1987, p. 7). He added that at age 21 he had his own secretary, a very good salary, and enjoyed a rather pleasant social life.

When the Germans occupied Italy in the fall of 1943, Val and his mother, with the help of smugglers, entered Switzerland illegally. They were interned in refugee camps for three months, after which they were sent to live with Val's father in Lausanne. Val studied at the University of Lausanne, receiving a degree in chemical engineering, and then a master's degree in physical chemistry, doing an experimental thesis on radioactivity.[2] A high point of his studies were courses that he audited in theoretical physics, taught by E. C. G. Stueckelberg von Breidenbach, an undervalued genius who anticipated important developments in quantum electrodynamics. He had a very important influence on Val, who said that the courses were "pure delight."

Around this time Val realized that his ambitions were more in the direction of physics than chemistry, and so he applied to study with Paul Scherrer, the head of the Physics Institute at the Eidgenössiche Technische Hochshule (ETH) in Zürich. However, he was rejected and in despair turned for help to Stueckelberg, who responded by calling Scherrer, and later introducing Val to him at a Physical Society meeting in Zürich. Some days later Val received an invitation to enroll at ETH.

He began in the fall of 1946 to work in Scherrer's nuclear physics group at ETH as a radiochemist, while attending courses in physics. When the teachers found that Val always solved the homework problems that were assigned to the physics graduate students (astonishing for a chemist), they made him a teaching assistant. Wolfgang Pauli, who had recently returned to ETH after spending the war years in Princeton, gave courses in classical theoretical physics. Val also attended lectures at the University of Zürich by Gregor Wentzel (later Val's colleague at the University of Chicago). None of the courses dealt with quantum physics, even though Schrödinger had invented wave mechanics in Zürich. Val was especially in awe of Pauli, who nevertheless proved to be friendly, inviting Val to social occasions, where he met some of Pauli's graduate students, including Res Jost, Felix Villars, Roy Glauber, David Peaslee, and Quinn Luttinger. Pauli was an examiner at Val's Ph.D. examination. Val wrote, "The fact that Pauli never treated me like an idiot during five years was one of the greatest encouragements of my graduate student life" (Telegdi, 1987, p. 12).

Having little experience with nuclear physics equipment, such as electronics, in comparison with the other graduate students, Val did his first experiment by examining microscopically the tracks that nuclear particles left in fine-grained photographic emulsion coated on glass (nuclear emulsion). Marietta Blau and Herta Wambacher had used this technique for cosmic rays studies in Germany in 1937, and in the 1940s physicists, especially at the University of Bristol, improved it and made important discoveries, including new elementary particles. Val and another student, H. Hänni, looked for characteristic patterns (stars) of developed grains in the developed emulsions, corresponding to the reaction

$$^{12}\mathrm{C} + \gamma \rightarrow 3\ ^{4}\mathrm{He}.$$

The 17.6 MeV gamma rays came from 440 MeV protons produced by a Cockroft-Walton machine bombarding a ^{7}Li target. Telegdi and Hänni analyzed the stars formed by the three alpha particles, and showed that the reaction occurred mostly through an intermediate state, the first excited state of beryllium plus one alpha particle.

Val reported this experiment in his first published paper in 1948 and it formed the basis for his Ph.D. thesis (1950). Over the next few years he studied photonuclear reactions, broadened his knowledge of physics, and developed a style of experimentation that included a deep understanding of technique marked by economy of means and cooperation with others.

After the emulsion experiment, Val set out to understand the theory of photonuclear reactions. He asked, for example, how the spin of the excited decaying beryllium nucleus led to angular correlation of the three alpha particles. To answer this question he studied the group theory of quantum mechanical angular momentum with the help of Mario Verde, a young Italian teaching assistant at Scherrer's institute. Verde was a graduate of the *Scuola Normale Superiore* in Pisa, had worked during the war years with Werner Heisenberg in Leipzig, and had earned his Ph.D. at Rome with Giancarlo Wick. A few years later he became a full professor in Italy at age 30. Verde tutored Val in quantum mechanics and became a lifelong friend (1949).

Recognizing his good work, Scherrer arranged for Val in the fall of 1948 to visit Cecil Powell's nuclear emulsion group at the University of Bristol, a major center of cosmic-ray research. Powell, Giuseppe Occhialini, and Cesare Lattes had used emulsions to discover the pi meson (now pion) that Hideki Yukawa had proposed in 1935 to be the analogue of the photon for the strong nuclear force. They had also observed that the stopping pion decayed into an unexpected new particle that they called the mu meson (now muon); that particle decayed into an electron. (Val was later was to make his most important discovery by studying closely this decay chain in emulsion.) Donald Perkins and Peter Fowler were members of Powell's group, as well as Richard Dalitz, who would become Val's colleague at the University of Chicago. Val continued his work with photonuclear reactions in emulsion, which he exposed to the gamma rays produced by a new 20 MeV electron synchrotron accelerator at Malvern, near Bristol. On his return to Zürich he continued these experiments, together with their theoretical analysis.

After the war many great physicists, such as Schrödinger, Bethe, Rabi, and Feynman visited ETH. Val often engaged them in conversation, which was perhaps resented by his fellow graduate students, but served to increase his self-confidence. In the fall of 1947 he met his future wife, Lidia Leonardi, in Zürich. Another person who was to play an important role in his life was Viktor Weisskopf, on sabbatical leave from the Massachusetts Institute of Technology as a guest professor at ETH in 1951. At the celebration of Val's 65th birthday at CERN in Geneva, Weisskopf recalled his impression that Val was "well-acquainted with most of the work going on in Scherrer's laboratory and also with some theoretical work of Pauli." He continued:

> One day he asked me whether my wife and I would like to have dinner with him. . . The dinner was better than we ever expected. I do not know whether this event was a kind of test, but the fact is that his marriage was a great success. . . All of us who are acquainted with Lia know about her intelligence, charm, and other qualities, but all of us who are acquainted with Val know that her great art of cooking did not play a secondary role (Winter, 1988, p. xxv).

When Weisskopf left Zürich, he told Val that he would try to arrange a position for him at MIT. However, as no position was open at that time, Weisskopf wrote that he had recommended Val to Enrico Fermi at the University of Chicago. With the approval of Gregor Wentzel, who had moved to Chicago from Zürich, Fermi made the offer. Val was delighted to accept it, and he remained at that institution for the next 25 years.

He counted himself particularly fortunate to be able to work at what he regarded as the Mecca of physics, under the leadership of Enrico Fermi. After supervising the construction of the world's first nuclear reactor from 1942 to 1944 in Chicago and working on the atomic bomb at Los Alamos, in January 1946 Fermi returned to Chicago with a group of other distinguished physicists, including Willard Libby, Leo Szilard, Edward Teller, and Harold Urey, and some younger associates. The university established three new physics research centers, Fermi's being called the Institute for Nuclear Studies (now the Enrico Fermi Institute). In July 1946 the Argonne National Laboratory was established in Argonne, Illinois, under contract with the University of Chicago. Fermi and his colleagues, Herbert Anderson and John Marshall, built a 450 MeV synchrocyclotron, capable of producing pions. For several years after it came online in 1951 it was the world's highest-energy accelerator. The institute also acquired a betatron that produced high-energy electrons.

We can sense Val's feelings about his new "boss" in what he wrote many years later:[3]

> No single individual in this century has contributed so much to physics, through theory as well as experiment, as did Enrico Fermi. Still, in this writer's opinion, his greatest contribution in the Chicago period lay in his teaching. Through his students and their teaching, the Fermi spirit is still alive today.

The many brilliant physics students at Chicago during this period included future Nobelists Jack Steinberger, Tsung Dao Lee, Chen Ning Yang, Owen Chamberlain, and Jerome Friedman. Others became almost equally prominent.

When Val arrived in Chicago in 1951, the Chicago synchrocyclotron had just begun operation and was the main focus of attention in the Fermi institute. However, Val chose to use the relatively neglected betatron to continue the research that he had begun in Zürich. The electron accelerator produced higher-energy photons than those he had worked with previously, and it allowed him to work independently. Through 1956 he published five papers on several photonuclear reactions in emulsion and two on the scattering of 30-90 MeV gamma rays by liquid hydrogen. He also collaborated with Murray Gell-Mann and with D. C. Peaslee on the theoretical implications of the charge independence of nuclear forces for photonuclear reactions (1953). This work depended on the isospin symmetry of nuclear forces, a forerunner of what would become for Val (to say nothing of Gell-Mann) a lifelong interest in the principles of symmetry in elementary particle physics.

After Fermi died in 1954, Val headed the nuclear emulsion group, which included Riccardo Levi-Setti. One of Fermi's doctoral students doing experiments was Jerome Friedman, who continued his work with emulsions and was awarded his Ph.D. in the spring of 1956. Val spent three months as a visitor at the Institute for Advanced Study in Princeton, New Jersey. When he returned to Chicago, he began an emulsion experiment with Friedman that many colleagues deemed to be a long shot, but turned out to be very important in what became known as the "parity revolution."

Until the mid-1950s physicists had assumed that the symmetry properties of ordinary space and time that held for the laws of classical physics (including special relativity) also characterized the quantum theory. These symmetries consist of continuous translation and rotation in space and translation in time. In addition, the classical laws of mechanics and electrodynamics are invariant under the discrete transformations: reflection in space P, formal reflection in time T, and the exchange of signs of positive and negative electric charge C. (T actually refers to the reversal of all particle velocities in a physical process.) These symmetries do, in fact, hold for the quantum version of electrodynamics (QED) and for the strong nuclear force responsible for the binding of nuclei, but the situation was much less clear for the weak nuclear interaction responsible for nuclear beta decay.

By April 1956 as discussed in the Sixth Annual Rochester Conference (one of a series of the most important international conferences discussing high-energy physics), unstable particles called K meson, or kaons, about half as massive as protons, were shown to have a puzzling behavior that might threaten the usual symmetry assumptions. The kaons, "strange" particles first observed in the cosmic rays and then produced and studied at accelerators, could be positive, negative, or neutral and decayed in a variety of ways (e.g., into two pions or three pions). Richard Dalitz, using a graphical method that he invented in 1953, had made a thorough and painstaking investigation of the world's data on the final decay states and showed that they had different properties under the sign of parity P (i.e., space reflection). Thus, either there were two kinds of kaons, having opposite P, or the law of invariance of parity did not hold for the interaction responsible for the decay, which was assumed to be similar to the nuclear beta decay interaction. However, the two kinds of kaons seemed to have the same mass and lifetime.[4]

Soon afterward Tsung-Dao Lee and Chen Ning Yang came to the conclusion that parity had not been experimentally tested in any weak interaction. They proposed that several weak interaction processes (other than the kaons) should be looked at for possible violation of the conservation of

P. At the National Bureau of Standards (NBS) in Washington, D.C., Chien-Shiung Wu of Columbia University and an NBS group conducted one of these experiments, involving the beta decay of a polarized ^{60}Co nucleus, and found that it violated the mirror symmetry P. Another suggested process was the charged pion decaying into a muon and a neutrino, followed by muon decay into an electron and two neutrinos. Richard Garwin, Leon Lederman, and Marcel Weinrich studied this at the Columbia University cyclotron, using electronic detection, and they also found evidence for parity violation. Earlier, in October 1956, Telegdi and Friedman had decided to examine the same process in nuclear emulsion, using positively charged pions from the Chicago synchrocyclotron[5] (1957[1][2]).

The Chicago experiment was simple in principle and found clear proof of parity violation. Positive pions are brought to rest in 1-mm-thick nuclear emulsion, each decaying into a positive muon and a neutrino. The muon comes to rest and decays into a positron and two neutrinos. After development, the emulsion is scanned under a microscope, the particle tracks are measured, and the space angle θ between the original direction of the muon and the positron's track is measured. If parity is conserved in either of the two successive decay processes, the distribution in θ must show backward-forward symmetry. To the contrary, they found pronounced asymmetry, the size of the effect proving that parity is significantly violated in both decays.

Compared with the electronic experiment, the emulsion technique is time consuming, since it requires the microscopic measurement of each decay. The emulsions must be carefully shielded from magnetic fields during exposure. Even the small stray field outside the cyclotron could cause precession of the muon's magnetic moment, which would have wiped out the observed asymmetry. This happens in part because the positive muon can pick up an electron in coming to rest and form a kind of exotic hydrogen atom called "muonium," which has about 100 times as large a magnetic moment as the muon.

The work was also slowed because Val had to leave the country in late fall when his father died in Milan, Italy, and he went there to help his mother cope. Still, upon his return, he found that Friedman had 1300 measured events and clear evidence for parity nonconservation. The result was definite but preliminary (they were aiming for 2000 events) but the competition was fierce and they decided to publish.

Friedman and Telegdi communicated their result to *Physical Review Letters* for fast publication. However, while the editors decided to publish the Columbia-NBS experiment and the Columbia cyclotron result the same week, they delayed the Chicago announcement until the next issue, where it appeared with a note (after protest) stating that it had been delayed "for technical reasons." This event caused Val great unhappiness that was only partly compensated by his receiving the Wolf Prize in 1991, in large part for this important work.

The prototype of the weak interaction is radioactive beta decay, which involves the decay of a neutron bound in a nucleus. It had been shown on very general theoretical assumptions that in any permitted interaction the combined symmetry operation CPT is conserved. If time invariance T holds, then the noninvariance of P implies also the noninvariance of charge conjugation C.[6] The parity revolution thus suggested that symmetries previously taken for granted must be tested experimentally, and this became one of Val's chief interests.

Of the many examples of nuclear beta decays, the simplest is the decay of the free neutron itself into a proton, electron, and a neutrino. To observe any symmetry violation in the decay it must be in a known polarized state. Val and a small group that he organized at the Argonne National Laboratory, near Chicago, used a beam of low-energy (thermal) neutrons from a research nuclear reactor, which was polarized by reflection from a magnetized metallic “mirror.” The decay was identified and measured by the detection of the proton and the electron by appropriate counters. Over several years the group obtained important results bearing on the structure of the nuclear weak interaction (1957[3], 1958, 1960). They were able to conclude that in beta decay, parity was not an invariant operation, and that there was no observable violation of time reversal invariance. Of four types of interaction consistent with constraints imposed by special relativity, they found a distinct preference for two of these (vector and axial vector) being present, with a relative absence of the other two types (scalar and tensor).

Another example of weak interaction involves the muon, which like the electron has only electromagnetic and weak but not strong nuclear interactions. For about 15 years Val studied the muons that were the decay products of the pions produced by the Chicago synchrocyclotron. He compared the electromagnetic properties of the muon to those of the electron to determine whether it is really only a heavy electron, as generally thought. He also studied the muon’s weak interaction, which is responsible for its production from pions, for its own decay, and also for its capture in atomic nuclei. Because of their electric charge, muons interact with electrons in scattering and also in forming muonium. Negative muons can be captured by atoms to form exotic atoms, and they penetrate into a heavy nucleus to form an exotic nucleus. All this makes a rich field for exploration, and Val became so identified with it that in some circles he became known as “Mr. Muon” (Hargittai, 2004, p. 168).

A mu-mesonic atom is an ordinary atom with an electron replaced by a negative muon. Because the Bohr radius is inversely proportional to the mass of the bound particle, the muon's wave function is concentrated near the nucleus, well within the electron shells of the atom. In heavy atoms the muon is within the nucleus itself and captured in a time smaller than a microsecond, about the lifetime of the free muon, but long enough for the muon to reach its atomic ground state.[7] In lighter elements, such as C, F, or Al, there is a competition between decay, which yields an electron, and nuclear capture, leading to nuclear disruption, gamma rays, and neutrons. The ratio of capture and decay rates provides a test for the form of the weak interaction responsible for the nuclear capture. The most important test involves the alignment of the spin of a muon to that of the nucleus, which in atomic parlance is called "hyperfine structure."

In a series of papers during 1960-1962 Val and his collaborators studied the theory of muon capture (1961[2]) and investigated the ratio of capture and decay experimentally in a number of light elements (1961[3], 1962). Among their conclusions was that muon capture in nuclei was indeed a weak interaction with maximal parity violation that favored a particular mixture of vector V and axial vector A interactions, conventionally denoted as V-A.

In addition to many mu-capture experiments and a detailed study of the electron spectrum in muon decay, Val worked on the decays of the strange particles (especially the neutral K mesons) and weak interaction effects known as second-class currents and weak magnetism. In 1983 he published an article describing a direct measurement of the helicity (i.e., right-handed or left-handed spin) of the neutrino involved in muon capture, which was analogous to a similar measurement for the beta decay neutrino that was performed two decades earlier by Maurice Goldhaber, with whom Val shared the Wolf Prize in 1991 (1982).

In addition to its weak interaction, the muon interacts electromagnetically with other elementary particles by virtue of its electric charge and magnetic moment. Is it just a heavy electron, a pointlike particle obeying the Dirac equation or has it structure or interactions that the electron does not have? And why does it exist? As I. I. Rabi famously asked, “Who ordered it?” Those were questions that Val tried to answer.

One promising system was muonium, an exotic atom consisting of a positive muon and an electron, analogous to positronium. Vernon W. Hughes at Yale University, an expert on positronium, had first studied it and Friedman and Telegdi dealt with muonium in their first parity experiment. In a series of experiments at Chicago, Val’s group measured with high accuracy the hyperfine energy splitting of the ground state of muonium corresponding to the alignment of the spin and magnetic moment of the electron and the muon being either parallel or antiparallel (1970, 1971). The resulting analysis of the results of the Chicago group gave an accuracy for the measurements of the muon magnetic moment to better than one part per million, providing a confirmation that the muon is a Dirac particle like the electron. It also provided an accurate new measurement of the fine structure constant α, a confirmation of the validity of the renormalization theory of quantum electrodynamics (QED) and, by comparison with the hyperfine energy splitting in hydrogen, a limit on the polarizability of the proton.

In addition to the muonium-based measurement of the muon magnetic moment, a more direct method is also highly desirable. In the case of the electron such experiments have shown that QED is the most precise of all physical theories. When the magnetic moment of a particle (measured in a unit called the “Bohr magneton”) is divided by the spin, the result is a dimensionless number called the gyromagnetic ratio g. For a Dirac particle g is exactly 2, but interaction with the particle’s own electromagnetic field produces a “correction” of about one part per thousand called the “anomaly,” which is calculated using QED with enormous accuracy. A precise measurement of g–2 provides a stringent test of whether the muon is a heavy electron.

To measure its magnetic moment is complicated by the muon’s microsecond lifetime, which is effectively lengthened in the laboratory by relativistic effects when the muons move with very high velocity, confined by a magnetic field. CERN has carried out for decades a series of dedicated experiments to measure g–2 of the muon.[8] Val was a leader of the pioneer group that set up the first of these, together with his good friend Richard Garwin, a Ph.D. student of Fermi’s at Chicago, who had been a member of one of the first Columbia parity experiment teams (1961[1]).

While on sabbatical leave at the Institute for Advanced Study at Princeton in the spring of 1956, Val had already given serious thought to observing the precession of the muon spin as it moves through a constant magnetic field at high velocity. He discussed this problem with theorists Valentine Bargmann and Louis Michel and the result was a much cited paper on the subject (1959). Using the theorem that quantum expectation values of an operator obey the classical equations of motion for a physical observable, they found such an equation for arbitrary spin in the relativistic case, now known as the “BMT equation.” One result was an expression for the rate at which the longitudinal polarization with respect to the muon’s direction of motion changes to transverse polarization. It shows that this precession is proportional to g–2.

The strange mesons called “kaons” that led to the discovery of P And C violation in weak interactions had other lessons to teach. They could be produced copiously by the strong nuclear interaction as antiparticle pairs of opposite strangeness, either charged K^+ and K^- or neutral K^0 and $\overline{K}^0$. The neutral particles decayed either into two pions, with a short lifetime, or into three pions, with a lifetime about 100 times longer. They thus acted as a mixture of two kinds of particles, called K_S (for short) and K_L (for long). Theorists explained this astonishing result as a particle-mixing phenomenon: The short-lived kaon was the sum of the two neutral antiparticles and the long-lived kaon was the difference.[9] Such things are actually permitted in quantum theory. Another surprising result was that in a neutral beam from which K_S had already mostly decayed, because the strong interactions of K^0 and its antiparticle are different, scattering regenerates the K_S component.

In the mid-1960s the violation of CP was discovered as a small effect, through the regeneration of K_S from a K_L beam without any scattering. With Val’s long interest in parity violation it was natural for him to consider what he could contribute to the understanding of CP noninvariance. To this end he launched a program at the zero gradient synchrotron at nearby Argonne National Laboratory. The most significant measurement was a precise determination of the phase of the CP violating K_L to $\pi^+\pi^-$ amplitudes. This was important for determining the nature of the CP violation (1969).

Val’s interest in neutral kaons continued in further experiments carried out at the newly built National Accelerator Laboratory (now Fermilab) at Batavia, Illinois. Val proposed to do precision measurements of neutral kaon regeneration, for which there were definite predictions from theory. A key feature was the measurement of both the magnitude and the phase of the difference between the K^0 and $\overline{K}^0$ amplitudes.

Of all the topics in the initial proposals to the lab, the study of kaon regeneration was probably the most popular, as there were five such proposals. Director Robert Wilson chose Val's proposal on the recommendation of the Physics Advisory Committee. The experiments were successful, focusing on carbon and hydrogen targets and showing that the scattering amplitudes were consistent with theoretical expectations. Val left for Europe in 1976 but stayed involved in further measurements carried out by the group he had formed, using the same apparatus. They measured, among other things, the atomic-number dependence of regeneration and the charge radius of the neutral kaon. This program continued at Fermilab for another three decades (1979[1,2,3]).

At CERN Val initiated the experiment NA10, one of a number carried out from the late 1970s to the mid-1980s in order to understand hadron-hadron collisions, which Richard Feynman said resembled colliding watches. At these energies both projectile and target acted as composite objects (quarks and gluons) having strong interactions. Experiment NA10 extracted unique information by looking at quark-antiquark annihilation into muon pairs (the Drell-Yan process). This was a subject and methodology new to Val, and he had to rely on more junior scientists. However, he continued to attract good people to work with him and his love for precise and incisive measurement was clearly present (1985[1], 1986).

During his career Val became known as an outstanding lecturer, and he was an internationally welcome colloquium speaker. Among his prestigious lecture series he served as Loeb Lecturer at Harvard, Page Lecturer at Yale, Schiff Lecturer at Stanford, Sherman Fairfield Distinguished Scholar at Caltech, and Visiting Professor at CERN. In 1995 the American Physical Society awarded him the Julius Lillienfeld

Prize in recognition of his skill in communicating the ideas of physics. He prepared his lectures meticulously, and his presentation was always original. From early on he had a very strong interest in the history of physics, especially that of the twentieth century. He collected anecdotes from and about the legendary figures, some of them his personal friends and acquaintances. His knowledge, his witticisms, and especially his enthusiasm never failed to stir his audiences.

In the 1980s he began to spend part of each year at Caltech, where he joined his old friends from Chicago, Murray Gell-Mann and Marvin Goldberger and his newer friend Richard Feynman. He also began to lecture on physics history at conferences (1987, 1989) and published articles on historical subjects (2000, 2002), while continuing his participation in experiments at CERN. For some years he was a member, then chair, of CERN's Scientific Policy Committee.

Val was a member of the National Academy of Sciences and the American Academy of Arts and Sciences. He was a foreign member of the Royal Society (U.K.) and also of the national academies of France, Hungary, Russia, and Sweden, as well as of the *Academia dei Lincei* (Italy). The University of Chicago awarded him an honorary doctorate. Val shared the 1991 Wolf Prize for Physics with Maurice Goldhaber.

CERN and ETH jointly sponsored a symposium called Festi-Val in Geneva on April 6, 1987, to mark Val's 65th birthday. It was a day of celebration for many of his friends and colleagues from around the world. (Winter, 1988). Val and Lia's marriage was childless, but Val left the world a legacy in his students and the colleagues whose lives he influenced. He made many contributions to experimental physics but also to theory and historically, and was thus a physicist's physicist and a real exponent of the culture of science.

I conclude by quoting from a tribute given by Jerome Friedman, one of the speakers at a memorial seminar to Val at the University of Chicago in January 2007:

> He was truly a unique figure in the world of physics. He was a brilliant physicist who made outstanding contributions to our field. He was also a wonderfully colorful personality and a man of enormous integrity who told us the truth even if sometimes we didn't want to hear it. He was not satisfied with easy, not well thought out answers. His probing questions often forced others, theorists as well as experimentalists, to think more deeply about the issues they were discussing. But he demanded as much of himself as from others. And he could be quite self-critical as well as self-deprecating. In 1972, when the University of Chicago named him the Enrico Fermi Distinguished Service Professor, he was sufficiently embarrassed by the honor to apologize to Fermi's widow. He was such a complex and memorable personality that I think that anyone who met Val just once would never really forget him.

I WOULD LIKE TO express my gratitude to Bruce Winstein and Roland Winston, who have helped with some of the writing. For their friendly help and support in producing this memoir I also thank Judith Goodstein, Lev B. Okun, Jerome Friedman, and I owe a special thanks to Lia Telegdi.

NOTES

1.M. Hargittai. In an interview: "Q. What was [your parents'] religion? A. Well, I suppose that my mother was clearly Jewish and my father only remotely." Also: "Q. Do you feel Jewish? A. Rarely," 2004, p. 182.

2.According to Lia Telegdi, while a student in Lausanne, Val performed as a stand-up comic in a well-known night club, pulling up his hair into horns and calling himself Mephisto.

3. V. L. Telegdi. Enrico Fermi. In *Remembering the University of Chicago,* ed. E. Shills, p. 122. Chicago: University of Chicago Press, 1991.

4.No one at the Rochester Conference was heretical enough to conclude that parity was "not a good quantum number," but Richard Feynman asked a question that had been posed to him by Martin Block: "Is it possible that parity is not conserved?"

5.An excellent survey of the these and other experiments on parity nonconservation is V. L. Telegdi: The earliest experiments leading to the V-A interaction. In *Pions to Quarks,* eds. L. M. Brown, M. Dresden, and L. Hoddeson, pp. 464-484. Cambridge: Cambridge University Press, 1989.

6. T. D. Lee, R. Oehme, and C. N. Yang. Remarks on possible non-invariance under time reversal and charge conjugation. *Phys. Rev.* 106(1957):340-345.

7.This ground state is like a miniature hydrogen atom.

8.These experiments have produced parts-per-million accuracy.

9.M. Gell-Mann and A. Pais. Behavior of neutral particles under charge conjugation. *Phys. Rev.* 97(1955):1387-1389. They used C to define the antiparticles, but it works as well for PC.

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