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SAM BARD TREIMAN
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A Biographical Memoir by

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Sam Treiman

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BY STEPHEN L. ADLER

SAM BARD TREIMAN WAS a major force in particle physics during the formative period of the current Standard Model, both through his own research and through the training of graduate students. Starting initially in cosmic ray physics, Treiman soon shifted his interests to the new particles being discovered in cosmic ray experiments. He evolved a research style of working closely with experimentalists, and many of his papers are exemplars of particle phenomenology. By the mid-1950s Treiman had acquired a lifelong interest in the weak interactions. He would preach to his students that "the place to learn about the strong interactions is through the weak and electromagnetic interactions; the problem is half as complicated.'' The history of the subsequent development of the Standard Model showed this philosophy to be prophetic.

After the discovery of parity violation in weak interactions, Treiman in collaboration with J. David Jackson and Henry Wyld (1957) worked out the definitive formula for allowed beta decays, taking into account the possible violation of time reversal symmetry, as well as parity. Shortly afterwards Treiman embarked with Marvin Goldberger on a dispersion relations analysis (1958) of pion and nucleon beta decay, a major outcome of which was the famed Goldberger-Treiman relation for the charged pion decay amplitude. Subsequent reformulations of their derivation led to the hypothesis of the partially conserved axial vector current (PCAC) and at a deeper level to our understanding of the spontaneously broken chiral symmetry of the strong interactions. A subsequent important PCAC application was made by Treiman and Curtis Callan (1966) in deriving the Callan-Treiman relations for K meson decay. Another widely quoted Treiman paper was his analysis with David Gross (1971) of scaling in vector gluon exchange theories, which anticipated the quantum chromodynamics treatment of this phenomenon and coined the now standard term “twist” for the difference between the dimension and spin of an operator. An important facet of Treiman’s research was his ability to devise simple, incisive experimental tests for important theoretical hypotheses. Prime examples are what became known as the Treiman-Yang angle test for single pion exchange dominance (the result of a 1962 collaboration with Chen-Ning Yang) and his paper (1972) with Abraham Pais giving the implications of weak neutral currents for inclusive neutrino reactions (which is how the existence of neutral currents was first established).

Equally important for Treiman’s impact on physics was his outstanding ability as a teacher and mentor to two dozen graduate students over three decades. Three of his students (Steven Weinberg, Callan, and myself) are members of the National Academy of Sciences and Weinberg is a Nobel laureate for his contributions to electroweak unification. Treiman’s students, building on his basic philosophy, contributed much to the current edifice of the Standard Model. Treiman’s teaching style has been termed Socratic. He was always willing to engage in a dialogue on any serious topic in physics, and one always came away from such discussions with valuable insights. For his contributions as an educator Treiman was honored in 1995 with the Oersted Medal of the American Association of Physics Teachers. Other honors included election to membership in the American Academy of Arts and Sciences and the American Philosophical Society.

PERSONAL HISTORY

Sam Treiman was born in Chicago to a first-generation immigrant family. His father, Abraham, had come to the United States from Lithuania and his mother, Sarah, from Russia, both before World War I. Sam had one sibling, a six-year-older brother, Oscar, who became an accountant. It is hard to improve on the vivacity of his own description of his youth, given in the autobiographical notes that he submitted when he was elected to the Academy in 1972.

> The family lived in Jewish ghetto areas in Chicago, within a larger network of maternal relatives. Although my parents had little formal education, they attached high value to learning and provided an encouraging, if impoverished, environment. I attended local public schools. They were pretty awful, in retrospect, but I didn't know that at the time. In any case I did very well in school and did have several stimulating teachers. In high school I read a fair amount of mathematics and popular science, on my own, and traded insights with a few other bright students in a small circle. I edited the high school newspaper, played clarinet in the band, and otherwise spent my time aimless but content. Intellectual stimuli came chiefly from my brother, an uncle, and books.
>
> After high school, in 1942, I went into chemical engineering at Northwestern University, on a scholarship. This going to college was a first for the wider family and, to a considerable extent, for the neighborhood. I can't now reconstruct why I chose chemical engineering, but it seemed "scientific" and important in war time. The freshman physics course was taught by Hartland Snyder, a very colorful and talented fellow; and it occurred to me that physics was what I wanted. After two years at Northwestern I joined the Navy, received training in radar repair, and spent the last year of the war as a petty officer in the Philippines, where I fixed radars and did a prodigious amount of reading in the peaceful jungles—novels and science.

As is evident from these passages, Treiman was at ease with his background even though his natural talents propelled him far beyond it, and he had an unusual ability to cut through to the essence in all matters he dealt with, an ability that figured in his later great success as a mentor to a generation of young physicists. And as the passages also show, Treiman viewed himself and the events through which he lived with a charming and often understated wit that, in the words of Princeton University's memorial resolution, "lay at the heart of his persona and was an important factor in his effectiveness in debate and counsel: Sam's ability to see wry humor in the face of serious issues lightened many a difficult moment, gave warmth to all of us, and was something he took great pleasure in sharing."

In a second autobiographical piece, a beautiful, detailed account of his career in particle physics written for *Annual Review of Nuclear and Particle Science* (1996) Treiman attributed his choice of both Northwestern and a chemical engineering major to his teachers, who were motivated by wartime concerns. Although Treiman did not then know of Snyder's past or future accomplishments, the man who stimulated him to choose physics as a career had written with Oppenheimer the seminal paper on gravitational collapse to what are now called black holes and would later discover with M. Stanley Livingston and Ernest Courant (and independently, Nicholas Christofilos) the strong focusing principle on which all modern particle accelerators are based.

At the end of the war, with GI Bill support, Treiman moved on from the Navy to the University of Chicago as a physics major, completing his undergraduate education with a B.S. in 1949 and earning an M.S. degree in 1950. Chicago at that time was a remarkable place, with a physics faculty that included Enrico Fermi, Maria Goeppert-Mayer, Edward Teller, and Gregor Wentzel. Treiman's immediate predecessors were the stellar group of graduate students who gravitated to Chicago after the war, among them Owen Chamberlain, Geoffrey Chew, Richard Garwin, Goldberger, Tsung-Dao Lee, Marshall Rosenbluth, Jack Steinberger, Lincoln Wolfenstein, and Yang. They set a seemingly impossible expectation level for the students, including Treiman, who followed, who were themselves an exceptional bunch. When Treiman taught an introductory physics section, his students included Fred Zachariasen and Jerry Friedman. Treiman did "well enough" on the notoriously difficult Chicago exams, and supported by an Atomic Energy Commission predoctoral fellowship, wrote his doctoral thesis on cosmic ray physics under the supervision of John Simpson, receiving his Ph.D. in 1952.

Sam Treiman met his wife, Joan Little, during their student days at the University of Chicago, where she majored in educational psychology and worked with disturbed children at the Orthogenic School, under the supervision of Bruno Bettleheim. They married in December 1952, and had three children, Rebecca, Katherine, and Thomas. Sam was always very proud that all three of his children earned Ph.D. degrees, Rebecca in psychology (specializing in psycholinguistics) from the University of Pennsylvania, Katherine in health education from the University of Maryland (following up on a masters in public health from Johns Hopkins), and Thomas in economics from the University of Wisconsin at Madison.

The Treiman home at McCosh Circle was the scene of frequent dinner parties for students and colleagues, with wide-ranging conversation in which Sam's humorous streak had free rein; for a graduate student or junior colleague, being invited to one of these was a memorable point in the progression of one's career. Sam prided himself on being up-to-date on all the latest experimental developments in particle physics, and he was also an avid reader, particularly of history. He was a passionate tennis player, with a savvy kit of skills that defeated many players who thought they excelled him in strength or form.

Only a few years after his retirement, following more than 46 years of service to Princeton University and to the national and international physics community, Sam was diagnosed with leukemia. After a valiant, brave, and characteristically graceful and good-humored struggle, he died in Memorial Hospital in New York on November 30, 1999, at the age of 74. Scarcely six weeks before, during a period of remission from his illness, I had the honor to have Sam as an after-dinner speaker at my sixtieth birthday conference, which was held at the Institute for Advanced Study on October 16, 1999. This was to be his last public occasion; it was hard to imagine then, and to accept later, that he would be gone so soon afterwards.

PROFESSIONAL HISTORY

After completing his doctorate, Treiman moved in the fall of 1952 to Princeton University as an instructor. Apart from periods when he was on leave, he spent his entire academic career at Princeton, rising through the ranks to associate professor (1958-63), professor (1963-77), and Eugene V. Higgins Professor of Physics (1977 to his retirement in 1998). He also served Princeton as chair of the Physics Department (1981-87), and as chair of the University Research Board (1988-95). In both capacities he was a major voice in shaping the future of the university and its science policy.

Following naturally on his thesis in cosmic ray physics, Treiman associated himself with the cosmic ray group in Princeton, which had been set up a number of years previously by John Wheeler and then was under the leadership of George Reynolds. Their activities focused on the new particles (e.g., K mesons, Lambda hyperons) that were being found in cosmic radiation. Treiman worked as house theorist for the group, writing papers on how to extract such information as particle spins and parities from the observed production and decay distributions.

This work led over a few years to a shift in Treiman's focus from cosmic rays to the new particles and their properties and in particular to the weak interactions responsible for their decays. Among his significant early particle physics papers were an analysis with Wyld (1955) of K meson decay accompanied by radiation of a gamma ray and an analysis with Robert Sachs (1956) of the K meson decay channel into pion, lepton, and neutrino. He also began a lifelong friendship and collaboration with Abraham Pais, who was then at the Institute for Advanced Study, studying such topics as the spectral structure of K meson decays (1957). After the parity revolution of 1957, in which it was discovered that the weak interactions do not respect left-right reflection symmetry, Treiman with Jackson and Wyld re-analyzed nucleon beta decay (1957), allowing for the presence of all of the four Fermi coupling types and for time reversal violation as well. Testing for time reversal violation in nuclear decays became an important topic, and the results of their paper were widely quoted. Treiman's interest in tests for symmetry violations in weak processes continued throughout his career and surfaced later on, for example, in papers with Callan (1967) on signatures of time reversal violating vector triple product correlations and with Barry Holstein (1976) on tests for so-called "second class" or abnormal G-parity currents (which, in agreement with subsequent experiments, are absent in the current Standard Model).

Treiman's first two graduate students, Steven Weinberg and Nicola Khuri, completed their dissertations in 1957. Weinberg's thesis topic dealt with strong interaction effects in weak decays and Khuri's with the derivation of dispersion relations for nonrelativistic potential scattering by a wide class of potentials. In the course of his career Treiman had two dozen students; the complete list with dates of completion is: Nicola Khuri and Steven Weinberg (1957); Carl Albright (1960); Kenneth Edwards and Young Suh Kim (1961); John Bronzan, Binayak Dutta-Roy, and Paul Kantor (1963); Stephen Adler, Curtis Callan, and Alfred Goldhaber (1964); Jonathan Rosner (1965); Porter Johnson and Rein Uritam (1967); Herbert Chen (1968); Stephen Schutz, Kazuo Fujikawa, and Glennys Farrar (1970); William Shanahan (1972); Bennie Ward (1973); Robert Schrock (1975); Evelyn Monsay (1977); Cornell Chun (1978); Dean Preston (1980); and Michael Musolf (1989, joint supervision with Barry Holstein and Robert Naumann). A majority on this list are now prominent faculty members at universities in the United States and overseas, and their research has played an important role in establishing the current Standard Model of particle physics.

Treiman makes an illuminating comment on his philosophy of teaching in his memoir (1996).

> A word here about graduate student research "supervision." Khuri and Weinberg needed no technical support or supervision from me. It was in fact the other way round as they patiently guided me along in the intricacies of their investigations. That largely continued to be the case with a long string of subsequent graduate students. The great trick is to get good students in the first place, then ask them to teach you.

As part of Treiman's self-education a student could count on a succession of penetrating questions by Sam whenever they met, which either exposed fallacies (leading to a research track being abandoned) or developed a good but only half-understood idea into one with a firm conceptual base on which a project could be built.

Khuri's thesis topic was part of a larger Princeton effort in dispersion relations, which was spurred by the presence there of Goldberger, who had achieved a great theoretical and phenomenological success by his derivation of forward pion nucleon scattering dispersion relations (the particle physics analog of the optical Kramers-Kronig relations). Treiman participated in a number of aspects of the dispersion relations program. With Paul Federbush and Goldberger he carried out (1958) an extensive dispersion relations analysis of the nucleon electromagnetic form factors, and in a tour de force with Richard Blankenbecler, Khuri, and Goldberger (1960) he was able to prove the Mandelstam double dispersion relation representation for nonrelativistic potential scattering in the case of potentials that can be expressed as a superposition of Yukawa potentials (the same class used by Khuri earlier in his thesis).

The most significant dispersion relations paper by Treiman, which had far-ranging implications, was his dispersion relations analysis with Goldberger (1958) of charged pion decay into a muon or electron plus a neutrino. Using the pion off-shell mass as the variable to be analytically continued into the complex plane and making some astute approximations, they deduced a simple formula relating the charged pion decay amplitude f_π to the nucleon mass m, the pion-nucleon coupling constant g, and the weak axial vector coupling parameter measured in beta decay g_A,

$$gf_\pi = mg_A.$$

This relation, the famed Goldberger-Treiman relation, fit the data at the time and remains good to about 10 percent accuracy. In a subsequent paper (1958) Treiman and Goldberger used their approach to calculate the so-called induced pseudoscalar coupling constant relevant for mu meson capture by a proton, again with good agreement with experiment.

These unexpected connections between the strong and weak interactions attracted much attention, and were soon found by Yoichiro Nambu, by Murray Gell-Mann and Maurice Lévy, and by Kuang-Chao Chou to be derivable from simpler assumptions concerning the near conservation of the axial-vector current and its relation to the pion field, for which the acronym PCAC (partially conserved axial vector current) was later coined. In modern terms an exactly conserved axial vector current, together with the fact that the nucleon is massive and has no opposite parity partner, implies that chiral symmetry is spontaneously broken by the strong interactions, with the appearance of massless pions as the corresponding Goldstone bosons. There are then low-energy theorems relating pion emission or absorption amplitudes to amplitudes with one less pion, of which the Goldberger-Treiman relation for pion decay is the simplest. In actual fact there are also explicit chiral symmetry-breaking terms in the Standard Model (coming from the quark masses), and so the axial current is only approximately or partially conserved, but the various low-energy theorems implied by axial current conservation are still useful approximations.

The PCAC hypothesis coming out of the Goldberger-Treiman relation served as the axial-vector current counterpart of the CVC (conserved vector current) hypothesis for the weak vector current proposed in 1958 by Richard Feynman and Murray Gell-Mann. Together with the current commutator algebra abstracted from the quark model in 1964 by Gell-Mann, they formed the basis for the "current algebra" program, which led to many phenomenological successes in the period 1964-66. My thesis project with Treiman, and subsequent work deriving from it, played a pivotal role in these developments. Entitled "High Energy Neutrino Reactions and Conservation Hypotheses," my thesis had the original aim of exploring the simplest quasielastic and inelastic accelerator neutrino reactions. However, Treiman had educated me about the CVC and PCAC hypotheses, which at that point had few tests—as Sam would often point out, PCAC was supported by “only one number,” the success of the Goldberger-Treiman relation. With this stimulus the topic of my thesis broadened into finding further tests and applications of CVC and PCAC, suggested by the context of neutrino weak pion production. Before long, Sam was able to say “now there is a second number,” and after my derivation of a sum rule relating the axial vector coupling constant to pion nucleon scattering cross sections (also derived independently by William Weisberger), which Sam was one of the first to learn about, this number blossomed into a multitude. An important addition to the current algebra program was contributed by Callan and Treiman (1966), who applied the general methods to K meson decays, achieving a number of striking, experimentally successful predictions.

Beyond its immediate phenomenological successes the larger significance of PCAC and CVC, together with Gell-Mann’s current algebra, was that they refocused attention on quantum field theory methods, which had been in eclipse during the heyday of the dispersion relations program. More specifically, the non-Abelian structure of the Gell-Mann algebra, together with the near conservation of the currents implied by CVC and PCAC, was suggestive (to an astute few) of a gauge theory structure for the weak interactions as well as electromagnetism. This led rapidly to the work of Sheldon Glashow, Abdus Salam, and Steven Weinberg, and of Martinus Veltman and Gerard ‘t Hooft on non-Abelian electroweak unification using the group $SU(2) \times U(1)$, thus providing one of the two pillars of the current Standard Model.

One of the hallmarks of Treiman’s style in physics was his ability to find incisive experimental tests of the various hypotheses and theories currently under discussion within the high-energy physics community. The most famous example is his paper with Pais (1972) on signals for the neutral currents predicted by the $SU(2) \times U(1)$ electroweak theory, in which they focused attention on the neutral current inclusive process in which a neutrino incident on a nucleon produces a final neutrino and a spray of strongly interacting particles. They showed that this cross section is at least 0.24 times the corresponding charged current inclusive cross section, in which, instead of an outgoing neutrino, there is an outgoing muon. This result was the basis for the first experimental confirmation of the existence of neutral currents. Other equally incisive papers were another paper with Pais (1975) giving inequalities that soon ruled out heavy leptons as a source for recently observed dimuon events, a paper with Kenneth Johnson (1965) using a proposed approximate SU(6) symmetry of the strong interactions to give successful predictions for the forward elastic scattering and total cross sections of pseudoscalar mesons on protons, and a paper with Yang (1962) giving a characteristic signal for single pion exchange dominance, expressed as the prediction that the differential cross section should have a specific axis of rotational invariance.

Treiman was also active on more theoretical issues as well. Following the theoretical work of James Bjorken on scaling and its experimental discovery at the Stanford Linear Accelerator Center, Gell-Mann proposed the dictum that "nature reads the free-field theory books." Using the connection between the Bjorken scaling limit for the electroproduction inclusive cross section and the commutator of electromagnetic currents near the light cone, Treiman and Gross analyzed the extent to which this dictum was true in quantum field theory and found that in a formal sense it is satisfied for strong interaction theories with a vector gluon exchange dynamics. In the course of this work they laid the groundwork for the later analysis by Gross and Frank Wilczek and others of deep inelastic processes within the framework of quantum chromodynamics (or, as now abbreviated, QCD, the second pillar of the Standard Model), which is a vector exchange theory and leads to scaling as a first approximation, with calculable logarithmic corrections. In a quite different direction, I collaborated with Treiman, Benjamin Lee, and Anthony Zee on a paper (1971), using effective Lagrangian methods to turn the axial anomaly prediction for neutral pion to two gamma ray decay into a prediction for the reaction in which two incident gamma rays produce three pions, anticipating a more general relation between different anomaly-induced processes found not long afterwards by Julius Wess and Bruno Zumino.

One of the great events in physics in the mid-sixties was the 1964 discovery by Treiman's Princeton colleagues Val Fitch, James Cronin, James Christenson, and René Turlay of the failure of CP (charge conjugation times parity) symmetry in K meson decays. Sam was fascinated by this development, and in its aftermath wrote a number of influential papers on implications of CP violation. With Doug Toussaint, Wilczek, and Zee (1979) Treiman wrote one of the first papers on implications of CP violation for the production of the observed baryon asymmetry of the universe, within the context of grand unified models linking the electroweak and strong interactions. This work gave a concrete realization of earlier, prescient ideas of Sakharov. In yet another collaboration with his longtime friend Pais, Treiman wrote a phenomenological paper (1975) on CP violation in charmed meson decays, which was a forerunner of the current searches for CP violation in B meson factories.

In addition to his research articles Treiman co-authored several books of lectures on topics in high-energy physics.

After his retirement he wrote an insightful book on quantum mechanics for a mathematically literate but non-specialist audience, entitled *The Odd Quantum* (1999). This book was published by Princeton University Press during the month he died, and he had a copy with him on his last trip to the hospital.

Beyond his research and mentoring of students Treiman served the physics community and influenced unfolding events in other capacities. To quote again from his memoir (1996):

> But I do claim some credit for Bram (Pais)'s literary successes. During my incarnation as an associate editor of *Reviews of Modern Physics,* I invited him to write a historical piece on particle physics. Instead he produced an article on Einstein and the quantum theory. It was later vastly enlarged and transmuted into his highly acclaimed scientific biography of Einstein, *Subtle is the Lord*. Subsequently, he published *Inward Bound*, the originally conceived though greatly broadened history of particle physics in the twentieth century.

When Fermilab was set up by Robert Wilson in 1970, Treiman was invited by Wilson to direct the laboratory's theory group. Rather than leaving Princeton permanently, Treiman went to Fermilab on several extended leaves to get the theory group successfully launched. Treiman was also active on various accelerator program committees and served extensively on the Department of Energy's HEPAP (High Energy Physics Advisory Panel) and a number of its subpanels. In addition, he was an active participant in the JASON group, which consulted on national defense issues from its inception in 1960. He left Jason in the late 1960s, but rejoined again in 1979, and the regular trips to the JASON summer study in San Diego were an important part of his and Joan's annual calendar. Finally, Treiman and Joan were early participants in the CUSPEA (Chinese/U.S. Physics Examination and Application Program) conceived by Tsung-Dao Lee in

1980 to help facilitate the admission of mainland Chinese students to physics graduate education in the United States. He and Joan went to China in 1981, 1982, and again in 1988 to examine and interview prospective candidates for the program. In his memoir (1996) Sam noted:

> The experiences were memorable. In our first visit we encountered many older applicants whose education had been interrupted by the cultural revolution . . . By 1988 most of the students were young and on track . . . Altogether, over the period of a decade, the CUSPEA program brought close to a thousand mainland Chinese students to America and fostered Chinese-US physics contacts on a broader front.

In opening his memoir (1996) Treiman remarked: "Looking back now, I am convinced that my own trajectory in fact spans another Golden Age and that I have been luckily situated within it." The first Golden Age of twentieth-century physics saw the development of relativity, quantum mechanics, and quantum field theory and their early applications to atomic and nuclear structure. A second Golden Age saw the wartime development of nuclear energy and radar and the subsequent use of the new technologies that emerged in postwar basic research. The third Golden Age, in which Treiman participated as a theorist, phenomenologist, and mentor, saw the application of quantum field theory to organize masses of experimental data on subnuclear physics into today's Standard Model. Sam Treiman, both through his own keen research insights and through his extraordinary ability to communicate his love of physics and to catalyze the work of his students and associates, was a major figure in particle physics during this exciting period of synthesis.

THE INTRODUCTORY SECTION of this narrative is taken with minor changes from an obituary that I wrote for *Physics Today* (August 2000, p. 63.) Both in passages directly quoted above and in many other places I have used the biographical account supplied by Sam Treiman to the National Academy of Sciences and his beautiful memoir (1996) published in *Annual Review of Nuclear and Particle Science*. I have also benefited in preparing this narrative from my personal association with Sam and with many of his collaborators, first as his graduate student at Princeton from 1961 to 1964 and later as a colleague at the nearby Institute for Advanced Study from 1966 onwards. I wish to thank Joan Treiman for supplying family information and to thank Sarah Brett-Smith, Curtis Callan, Val Fitch, and Joan Treiman for reading a draft of this memoir.

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