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ABRAHAM PAIS
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A Biographical Memoir by
ROBERT P. CREASE

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Abraham Pais was a theoretical physicist during the first part of his career and a science historian during the second. Though born in Amsterdam and a Dutch speaker, he spent nearly all his career in the United States and was most comfortable in English. As a scientist he was a founder of theoretical particle physics and made seminal contributions to the theory and nomenclature of the new forms of matter being discovered after World War II. As a historian he had a sharp eye for the significant detail and touching anecdote, knew personally many of his biographical subjects, had a bold approach to narrative, and set new standards for writing science history. In the title of his memoir, *A Tale of Two Continents: A Physicist's Life in a Turbulent World* (1997), the phrase "two continents" is ambivalent, and simultaneously refers to several pairings: Europe and America, physics and history, science and the humanities, the life of the mind and the life of the world. He was a citizen of all these continents, appreciating and contributing to each. "Bram" to his friends, Pais was a cosmopolitan scientist and human being.

The subtitle of Pais's memoir mentions "turbulence." He experienced much of it during his life. As he wrote in *Two Continents,* his lifetime included

> Over 80 international conflicts, including 2 world wars, more than 120 new nations formed, 1 Great Depression, 1 U.S. president assassinated, 1 resigned, 1 black woman elected U.S. senator, 2 women appointed to the U.S. Supreme Court, 1 polio and 1 AIDS epidemic, 1 royal abdication, 7 men (or were there 8?) who married Elizabeth Taylor, over 300,000 new words added to the *Oxford English Dictionary* (including two created by me), a civil rights movement, a women's movement, billions of hamburgers sold at McDonald's, the beginning of space exploration, the invention of the microchip, the discoveries of DNA and of quantum mechanics—to give a pretty random sample. (1997, pp. xiii-xiv)

Coming from Pais's vigilant pen, this selection is not truly random. It reflects the global scope of his interests—ranging from science and politics to popular culture—as well as traces of his quirkiness, humor, and pride, as exemplified by the reference to his two contributions to the *Oxford English Dictionary*. Characteristically focused on the world around him rather than himself, this passage also omits mention of the personal turbulence that befell Pais during the Second World War, when he narrowly escaped death several times as a Jew hiding in the Netherlands during the German occupation.

EARLY LIFE AND EDUCATION

Pais was born on May 19, 1918, in Amsterdam, the city where all the paternal ancestors that he could identify—Sephardic Jews—were also born. The northern Netherlands was "the oldest emancipated post-Renaissance Jewish community in the Western world," Pais wrote, sometimes called "the Jerusalem of the North" (1997, p. 3). His father, a religious man, was a schoolteacher and headmaster of two schools, one a Sephardic Hebrew school; his mother gave up being a schoolteacher when she married his father. Pais's sister, Annie, was born two and a half years after him. Pais grew up in a "religious but strongly assimilated milieu." One day when he was about nine years old he lost all faith.

> It was on a Saturday afternoon. My parents were in the living room; the maid had the day off. Suddenly the thought came: What would happen if I lit a match—strictly forbidden on the Sabbath? I went to the kitchen, struck a match, blew out the tiny flame, and ran like hell. No ghastly repercussions. That was the end of that. I still feel it was a privilege to have gone through my liberation as a personal act. (1997, pp. 11-12)

Yet Pais distinguished between being Jewish and being religious, and retained what he called the tribal feeling of Jewish identity throughout his life. He became an active member of a Dutch Zionist youth organization (NZSO); most of his peers in it would soon be deported to German camps and would not survive. Through his Zionist connections he met Tineke Buchter, the non-Jewish friend of the sister of an NZSO peer. Tineke, exactly two years his junior, was a budding psychoanalyst and introduced him to Freud's works. Because Buchter was a *shiksa,* Pais's father would not let her in the house; still, the two fell in love and were soon all but engaged.

Pais loved literature and music, often attended the Amsterdam Concertgebouw by himself, and briefly considered becoming a conductor. Nevertheless, when he entered the University of Amsterdam in 1935, it was with vague ideas of a career in science. In the winter of 1936-1937 these interests were sharply focused by George Uhlenbeck, a professor at Utrecht and a codiscoverer of spin, who delivered two guest lectures. Calm, systematic, and unpretentious, Uhlenbeck took his audience through Fermi's recent theory of beta radiation together with an analysis of relevant experimental data. It was a revelation, Pais's first exposure to science at the frontier. "I had the intense experience that here and now it was revealed to me what I wanted to do, had to do. From that time on I have never wavered in that conviction" (1997, p. 18).

Pais completed his undergraduate work in Amsterdam, graduating in February 1938 with majors in physics and mathematics, minors in chemistry and astronomy. He was fortunate to learn from those physics giants who had been key figures in the quantum mechanics revolution of 1925-1932, but also fortunate that his education took place when the strife concerning these developments was a relic of the past, and strange quantum phenomena such as the uncertainty principle were simply givens. "I had no sense whatever at that time of the stir and struggle which, only ten years earlier, had accompanied the introduction of the new mechanics" (1986, p. 249). Pais convinced Uhlenbeck to take him on as a student, and commuted to Utrecht from Amsterdam. Uhlenbeck gave him Hendrik Kramers's textbook on quantum mechanics to study, followed by several theoretical problems. The following fall, when Uhlenbeck left to become a visiting professor at Columbia University in New York, Pais became Kramers's friend, and studied as well with Hendrik Casimir, another quantum pioneer who was delivering lectures at Utrecht.

Pais's contacts with laboratory experiments were few, but one was memorable: in February 1939 he read the now famous *Nature* paper by Meitner and Frisch, "Disintegration of Uranium by Neutrons: A New Type of Nuclear Reaction," and excitedly ran to tell his friends, who realized that they ought to be able to see the phenomenon, which the article's authors called "fission." The Utrecht lab had on hand all necessary equipment: pieces of uranium, a neutron source, an oscilloscope. Within minutes they saw huge spikes on the screen of a magnitude unexplainable within existing theories of the atomic nucleus. When Uhlenbeck returned from the United States, Pais studied fission with him, and the theory of electrons and positrons: "One of my life's strongest emotional experiences related to science occurred when for the first time I understood Dirac's equation for those particles" (1997, p. 35).

As part of his master's training Pais gave theoretical seminars. Emulating Uhlenbeck's clear and low-key style, he explained fission and the new particles found in cosmic rays called "mesons." Pais later concluded that Uhlenbeck, more than anyone else, taught him the mathematical techniques of theoretical physics, and in particular to use mathematics as a tool rather than an end in itself. "I have come to the conviction that a theorist can never know enough mathematics, yet, paradoxically, he can easily know too much of it" (1997, p. 37). In August 1939 Uhlenbeck left Utrecht again for good, replaced by Léon Rosenfeld. Before Uhlenbeck left he found Pais an academic appointment at Utrecht—modest, temporary—to replace an assistant named van Lier going on leave. "As a result, I now received my first salary, small but nevertheless most gratifying. And so it may be said that at age twenty-one, still only a graduate student, I began my academic career" (1997, p. 38).

"THE IMPOSSIBLE REAL": WARTIME

> I have often heard it said that witnesses to those past disasters believe it is impossible to really make clear to interested outsiders what he or she has experienced. I am no exception. When I hear myself talk to others about those earlier experiences of mine, I invariably have a peculiar sensation. I hear my own words, know that I speak the truth as honestly as I can, yet cannot believe what I hear myself saying. (1997, pp. 67-68)

The Second World War nearly ended both his career and his life. On April 28, 1939, Pais was both spellbound and terrified to hear German Chancellor Adolf Hitler deliver a two-hour radio speech—his last public speech during peacetime—publicly threatening war. Four months later, on September 1, 1939, Germany invaded Poland, with Britain and France declaring war on Germany shortly thereafter.

For almost nine months Pais's life was unaffected. On his 18th birthday Pais had been declared fit for military service but had received a deferment pending receipt of his master's degree. In fall 1939 he moved to Utrecht to work on the M.Sc., and passed the examination on April 22, 1940. Like most countrymen, he was in a state of blissful denial. "We lived in a little country that was intellectually alert, yet asleep, by and large, regarding the possible impact on us of international events. We lived complacently in a country with a very high standard of living, bourgeois and self-satisfied in outlook. How shortsighted we were" (1997, p. 46).

On May 10, 1940, two and a half weeks after Pais's M.Sc. examination, the German army invaded the Netherlands. The vastly outmatched Dutch army capitulated on May 15. Belgium fell on May 28, Paris on June 14, and the armistice was signed on June 21. Pais spent the day after the fall of Paris at Kramers's house outside Leiden. Paris—the symbol of Western culture—fallen to the Nazis! "I do not mean to exaggerate when I note that the fate of Paris had hit us harder than even the fall of Holland" (1997, p. 54).

In shock, many Dutch Jews committed suicide. Van Lier was one. Rosenfeld, who arrived in September 1940, approved Pais's appointment as van Lier's successor—there being no Dutch army to enlist in after the capitulation—and Rosenfeld set Pais to work on several problems for his Ph.D. Life for Dutch Jews grew worse. In November 1940, protests against dismissals of Jewish faculty led to Leiden's being closed, and Jews were barred from holding civil service (including university) posts, abruptly terminating Pais's position at Utrecht. Rosenfeld appointed a successor, secretly arranging for him to share his salary with the now unemployed Pais.

In 1941, restrictions imposed on Dutch Jews—who numbered about 140,000—began to extend to every part of life. It began on January 5 with what at the time seemed "a small ripple" (1997, p. 79): Jews were forbidden to go to the movies. Pais recalled signs sprouting in front of cinemas: "Für Juden verboten." A more portentous decree came on January 24: all Jews, full or part, must register and carry an identity card stamped with a large black J. "I cannot remember any Jew who realized at that time that this measure would set a mortally dangerous trap" (1997, p. 79). Harassment, strikes, violence, and deportations followed. In February the Germans rounded up several hundred Dutch Jews and shipped them to death camps. Pais, trembling with rage, witnessed street violence by German police against Dutchmen from Tineke's house in Amsterdam. In short order Jews were forbidden to move, possess radio sets, take public transportation, use bicycles, and enter certain public areas. Many Dutch gentiles joined in opposing the measures. Not losing his sense of humor, Pais was amused by the following piece of graffiti written by one Dutchman: Blijf met je moffenpoten van onze rotjoden af. "Keep your Hun's paws off our rotten Jews" (1997, p. 57).

Meanwhile, another German decree set July 14, 1941, as the date after which Jews would be forbidden to receive Ph.D. degrees. "Not," Pais wrote, "an ideal atmosphere for doing research" (1997, p. 41). Nevertheless, the deadline left him determined to finish and achieve some sort of victory, however modest, over the Germans. "Hell-bent as I was about getting the work done, I had little emotional energy to waste on the constraints of everyday life, nor on fearful anticipation of what might happen next. Indeed, my strong attachments to science provided me throughout the war years with a sort of protective emotional shield from the events around me" (1997, p. 41). Pais worked for weeks on end waking at 5 a.m. and writing all day, often until 2 a.m. the next morning. He made the deadline, defending his doctoral thesis on July 9, 1941 (1941). In the next two years Pais published four papers based on this work. He also met regularly with Kramers to discuss physics. Later in life, however, Pais would express regret at not having had a deeper and lengthier training in physics.

Dutch Jews began to suffer horribly. In 1942 all were forced to move to Amsterdam to live in a ghetto, and to wear yellow stars. That July came the first systematic deportations to labor and death camps. Stamps on ID cards could provide exemptions—all in the end temporary—from deportations. About four out of five of the approximately 140,000 Dutch Jews were murdered during the war. Pais's sister, Annie, was one, gassed in the Sobibor death camp in occupied Poland in June 1943. Pais's parents miraculously survived.

Those Jews who went into hiding were called *onderduikers*, or divers. Diving was expensive and dangerous.

> Every diver who survived has his or her distinct story to tell. Of being ever mindful of the constant dangers of discovery. Of loneliness and adjustment to a radical change in lifestyle, for diver as well as host. Of living in sometimes very cramped spaces. Of tensions with hosts, or among themselves if there were more than one, itself not a good idea. Of those who became ill or went mad, or even some who died. Of betrayals. (1997, p. 84)

Pais began to prepare to become a diver late in 1942 after the first deportations. He began to store clothing at Tineke's house, which was a refuge for Jews either hiding there or en route to other hiding places, and which received advance warning of Gestapo raids. He got a fake identity card, trained himself in physical exercises that could be done in confined spaces, and acquired a small set of dumbbells. At one point some friends planning an escape to Spain asked if he wanted to join. He declined, fearing that the journey would disrupt the physics research that he was still managing to conduct with Kramers.

In March 1943 Pais went into hiding in the attic of a home not far from where Anne Frank and her family were also hiding.[1] The attic had an additional tiny space behind the panel of a false wall into which Pais could squeeze and lock himself in. He paid the hosts with money from the sale of his father's stamp collection. He passed his time exercising and studying physics. Tineke, now a medical student at the University of Amsterdam, fetched him books from the university library. This was courageous and dangerous; rumors abounded that one way the Gestapo looked for divers was to see who took books from the library, and if for instance a medical student suddenly began taking out physics books it could trigger suspicion. Pais read not only physics but also novels: Tolstoy, for instance, and all of Dickens. He also regularly trained himself in rapidly entering and locking the hiding place.

Kramers came by regularly to talk about physics. The specific subject was usually quantum field theory, or the application of quantum theory to electromagnetic phenomena. At that time quantum field theory was plagued by a particularly obdurate problem known as self-energy. According to the theory, a charged particle interacts with its own field; think of how a moving boat can be rocked by its own wake. However, perturbation theory—the existing calculational technique of quantum field theory—yielded nonsensical results, predicting that the self-energy would be infinite. Kramers and Pais argued heatedly about how to resolve this seemingly intractable issue. Kramers wanted to start from a classical, non-relativistic theory of the electron, while Pais argued that self-energy is "inherently a quantum problem" (1986, p. 449) and a realistic finite theory had to incorporate quantum mechanics at the start. Kramers also gave Pais cello lessons; Kramers was proficient and had decided that Pais's extended confinement provided him an excellent opportunity to continue his musical education and learn to perform.

In November 1943 Pais was at dinner with his hosts and Kramers when the Gestapo raided the house. Pais dashed upstairs to the hiding place, but was too nervous to properly work the lock, and had to hold the panel in place by hand. It did not fit that way, and left a small crack. Soldiers entered the attic; one noticed the crack and shone in a flashlight. Then he left. "For the moment at least, I had escaped the most dangerous situation in my entire life" (1997, p. 107). Pais moved to Tineke's house, then to a second hiding place.

In September 1944 the Gestapo raided a house that Pais had dropped by for a brief visit with his mother. He survived by racing to the basement and diving beneath a pile of women's clothes to hide. In the next few months he moved to several other hiding places. That winter was horrifying. In *Two Continents* Pais struggled to convey both his emotional state and a believable account, decided that the task was beyond him, beyond providing a few details says simply, "words fail," (1997, p 70) and invoked the French philosopher Maurice Blanchot's phrase "the impossible real" (1997, p. 68). There was no fuel or soap, next to no food. "Have you ever tried horse steak? Tastes fine" (1997, p. 63). Fifteen thousand people died of hunger in northwest Holland alone. Dead bodies piled up in churches. After the war, Pais burned the diary he kept, trying to erase the painful memories—to regret it years later, with a new appreciation for memory, even of the horrific.

In March 1945 his hiding place, his fifth, was raided—the result of a betrayal evidently by an ex-girlfriend—and Pais and a comrade were captured and put in a Gestapo prison. Tineke frantically informed Kramers, who wrote Heisenberg asking if he could get Pais released. Heisenberg wrote back that he was "very sorry, but could not do anything" (1997, p. 121). At the end of April 1945 Tineke then risked her life. She located the address of a high Gestapo official in Amsterdam—a close friend of Hermann Goering—took a copy of Kramers's letter, and knocked on the door. Trembling, but in perfect German, she pleaded for Pais's release, explaining that he was only an apolitical scientist. It worked; Pais was released. His comrade was shot. "So it came about that I gained my freedom because of physics, and because of the devotion of Kramers and, above all else, of Tineke" (1997, p. 121).

On V-E day, May 8, 1945, a Canadian regiment entered Amsterdam, formally ending the German occupation. On June 30 Pais encountered several Canadian soldiers looking for an open bar. All bars were closed, but Pais offered to share his stock of alcohol with them. Taking them back to his apartment, he suddenly received a blow to the head, and awoke in a pool of blood with his whiskey, wallet, and watch gone. The next evening, he met Tineke at the Amsterdam Concertgebouw. Tineke and her family had managed to survive the occupation, though about a third of the Dutch protectors of Jews did not. Tineke was shocked to encounter Pais heavily bandaged and giddy. "He was laughing," she recalled. "He thought it was funny that he had survived the German occupation, only to be beaten up and robbed by his liberators."

The wartime events left a long shadow on Pais's subsequent career and life. The solitude, interrupted by intense discussions during intermittent visits from Kramers, habituated him to focusing on work and regarding everything else as a diversion. While as a student he had forced himself to concentrate, now "it all worked differently"; thoughts now came unforced, as if he were their passive receptacle. The experience gave Pais a comfort and intimacy with thinking that he found liberating. "That was the most important positive experience of my years in hiding" (1997, p. 109). He also had details permanently emblazoned on his memory: the words of songs sung by German soldiers, the number of his Gestapo jail cell (IB4). Later, after he had moved to the United States, he would meet again with Tineke, who would end up there as well. Yet the horrifying wartime experience also left him unable to fully engage in physics for a few years.

TUNING UP: FIRST YEARS IN THE UNITED STATES (1946-1949)

> [T]he state of particle physics…is…not unlike the one in a symphony hall a while before the start of the concert. On the podium one will see some but not yet all of the musicians. They are tuning up. Short brilliant passages are heard on some instruments; improvisations elsewhere; some wrong notes too. There is a sense of anticipation for the moment when the symphony starts. (1968)

In June 1945 Pais resumed his assistantship with Rosenfeld at Utrecht, and began to prepare papers based on his dissertation and studies he had managed to carry out while in hiding. One concerned his analysis of the self-energy problem in quantum electrodynamics that he had discussed with Kramers. Pais noted that if one added to the interaction of an electron with the electromagnetic field a coupling to a neutral scalar meson field the result would be a finite self-energy (1945). Though this novel theory had defects, Pais explored more implications in another paper, including an estimate of the difference between the mass of the proton and neutron (1946). Pais's logic was sound, but the method turned out not to be the right way. He also began expository writing. Following the explosion of the atomic bomb over Hiroshima in August 1945, he was asked to write a magazine article about the weapon, thus inaugurating him in the "important and difficult" task of writing about science for the general public, and making him "the resident Dutch expert of my generation on nuclear matters" (1997, p. 144).

Yet Pais was determined to leave the Netherlands, in search of more training and to help erase painful memories of the previous years. Rosenfeld recommended him to Bohr in Copenhagen and Pauli at the Institute for Advanced Study in Princeton. Both accepted Pais for short stays; he arranged to visit Copenhagen first, then Princeton.

On January 24, 1946, Pais arrived in Copenhagen as one the first postwar generation of young postdocs to visit Niels Bohr's Institut for Teoretisk Fysik, later renamed the Niels Bohr Institute. When he met Bohr, "My first thought was, what a gloomy face. Then he began to speak." The initial negative impression was abruptly replaced by an appreciation for his "intense animation" and "warm and sunny smile" (1997, p. 150). Pais's interests now included some short-lived particles (besides the familiar proton, neutron, and electron that comprise ordinary atoms) recently found in cosmic rays. While in Copenhagen, Pais collaborated with Christian Møller on a theory that would treat particles new and old not as fully independent objects but as member of families, then called "towers." To Pais's satisfaction this work produced a rudimentary formula that accounted for differences in masses between certain particles (1947). While the paper's conclusions were soon obsolete—information about the new particles was sketchy and confused—it made one small but permanent contribution: the authors lumped together all the light particles into one family and dubbed them "leptons," from the Greek for "slight." The name stuck and became the first of the two new words Pais coined that made it into the Oxford English Dictionary.

On September 4, 1946, Pais stepped aboard a ship bound for the United States, and arrived in New York City in time, two weeks later, for the first postwar meeting of the American

Physical Society. He gave a talk, and encountered Uhlenbeck and Kramers. During one session, Pais was sitting next to Kramers when the latter suddenly scribbled a note. "Turn around and pay your respects to Robert Oppenheimer." Pais did, to encounter the world-famous physicist whom Pais recognized from newspaper photographs, wearing a short-sleeved open shirt. "I felt I had entered a new civilization, where you call professors by their first names and where esteemed gentlemen appear in public wearing neither jacket nor tie" (1997, p. 186).

A few days later, on September 22, 1946, Pais arrived in Princeton. Presenting himself at the Institute for Advanced Study ("the institute"), he discovered that Pauli had returned to Zurich. He was disappointed, yet "[Pauli's] temporary presence in Princeton profoundly affected my career . . . since it caused me to spend the next 17 years in Princeton." Pais soon met other physics greats, including Paul Dirac, Albert Einstein, John von Neumann, and Bohr again. During Bohr's stay at the institute in 1948, Pais was able to witness Bohr and Einstein refighting the battles that surrounded the birth of quantum mechanics in the late 1920s—battles that Pais had been too young to know—and developed a sophisticated understanding of the ideas, even helping Bohr with his seminal account of his discussions with Einstein.[2] Pais learned to appreciate Bohr's quirky sense of humor and cryptic remarks, including: "Tomorrow is going to be a great day, because today, I don't understand anything!" Pais continued to converse with Einstein about quantum theory once every few weeks for the next nine years, frequently accompanying Einstein on his lunchtime walk home. These discussions, which were in German, lasted nine years, until just prior to Einstein's death. During one walk, around 1950, Einstein abruptly stopped, turned to Pais, and asked "if I really believed that the moon exists only if I look at it," thus starkly and dramatically posing “the central epistemological issue of quantum mechanics” (1982, p. 5).

Oppenheimer became director of the institute in April 1947. Seeking to build theoretical physics, he asked Pais to stay. Pais did, for 16 years. In 1949 he received a permanent appointment and in 1951 became a full professor, only the third physics professor after Oppenheimer and Einstein. Pais found Oppenheimer, one of the most complex public figures of the 20th century, not always easy to work with. Oppenheimer was renowned for treating speakers cruelly, and Pais found himself having to comfort several, some of them sobbing. Oppenheimer initially extended such treatment to Pais; Pais, however, was one of the few with the courage and self-confidence to talk back, saying something like, “I won’t take any longer your unwarranted behavior” (1997, p. 240). Oppenheimer never treated Pais the same way again. Pais’s colleague at the institute, Freeman Dyson, once described Pais as “a slow and solid character, evidently able to resist without effort Oppenheimer’s jitters.”[3] Pais was also one of the few individuals who could coax the ever-aloof Oppenheimer into relaxing. At a party one evening playing folk songs on a guitar, Pais insisted that Oppenheimer sit down on the floor and sing along just like everyone else. Oppenheimer complied, shedding his formidable “air of hauteur,” to everyone’s astonishment. “I was touched to see that his attitude of superiority was gone; instead, he now looked like a man of feeling, hungry for simple comradeship” (1997, p. 241).

Pais, indeed, was a pillar of the institute’s social community. He was keenly interested in other people, and had an extraordinary ability to listen. Many people came to him for help and counsel and spoke to him more about personal troubles than about science. He was widely recognized as the “house psychiatrist for the institute community,” Dyson says.

"Having himself such deep emotional scars, he was unusually sensitive to other people's problems."[4]

At the beginning of June 1947 Pais was one of the 24 participants at the Shelter Island conference, regarded by many present as the most memorable conference they had ever attended. It was for leaders in U.S. theoretical physics, though Kramers attended, as well as a few experimenters. Pais provides a striking description of the conference (1997, pp. 228-232; 1986, pp. 450-452). He also wrote an essay on quantum electrodynamics after the conference, intended as the introduction to a collection of papers on the subject. The book project was canceled because developments in quantum electrodynamics were too swift-moving, yet Pais's essay provided such a good summary of the subject that it was published by itself and is still a terrific historical snapshot of the state of the art (1948). Two successive conferences were held at Pocono Manor in Pennsylvania and at Old Stone-on-the-Hudson in upstate New York, where more progress was made on fixing the infinities, in a procedure now known as renormalization. After the Pocono conference, Oppenheimer relayed word of some Japanese wartime theoretical work that included the news that a physicist named Sakata had made the identical attempt to eliminate the infinities as Pais had, including a calculation of the neutron-proton mass difference.

During his first years in the United States, Pais worked on renormalization theory with Uhlenbeck (who also taught him squash). Still, Pais described his initial year at the institute as "unproductive," for "I was still suffering from postwar trauma" (1997, p. 203). For years he had nightmares that involved killing or being killed. In 1948 he entered psychoanalysis, purposefully seeking an analyst who was not American but European. He chose the Viennese-born Freudian psychoanalyst Theodor Reik, who had studied with and been analyzed by Freud himself, and in analysis underwent a painful reliving of the wartime experiences. The fact that Reik was European helped Pais immensely: during the analysis, words would fly in French, German, Dutch, Hebrew, and Yiddish. The encounters were stimulating to both Pais and Reik, who wrote of them, not using Pais's name, in his works.[5] At one point Reik remarked, "Doctor Pais, you are trying to be Moses and Jesus Christ all in one. Don't you think that is overdoing it?" (1997, p. 247).

PICKING GOD'S POCKET: THE BIRTH OF PARTICLE PHYSICS (1950-1957)

> Scientists are like pickpockets. God has all the secrets in his pockets, and we try to pick them. You make an assumption in science—and it is an assumption—that there are fundamental laws you can find out. You have an idea you think can be proved and you try to prove it. Depending on how it goes, you make a step forward or you make a fool of yourself. Nature doesn't care whether you're right or wrong. Nature is the way it is, and you had better be smart enough to get a little glimpse. (1997, p. 290)

After the war, physicists began to discover new types of particles in cosmic-ray showers. Some of these particles were relatively light, including the newly discovered π and K mesons, while other particles were heavy, with the Λ heavier even than the proton. These unstable particles had decay lifetimes much longer than would be expected from their high production rates. They were initially dubbed "V" or "strange" particles: "V" because of the forked tracks they made in cloud chambers, "strange" because they were easily produced but took longer than expected to decay. At first, Pais wrote, these new particles did not cause "any stir or immediate awareness of a new era being upon us in regard to the structure of matter" (1997, p. 267). Pais himself would be a major factor in creating that stir, and in ushering in that new era. "The arrival of the new particles," Pais wrote, "changed my life" (1997, p. 268).

Pais's attention was riveted by a paper published in 1950 that described 34 cloud-chamber photographs of strange particles, confirming earlier observations that "new unstable neutral and charged particles exist."[6] Startled by the news, Pais was thrilled to behold another, improved chance to put into practice his intuition that particles could be grouped into families. He all but ceased work on the renormalization of quantum electrodynamics—which was proving more fertile than its reputation, and a renormalization program seemed in good hands following the Shelter Island conferences and its two successors—to focus on particle physics. "Drop everything else, I told myself, and devote yourself to what must be the beginning of a new chapter in the story of the structure of matter. I did and it was" (1997, p. 268).

Pais had a particular modus operandi for picking God's pocket. The conventional approach to organizing particles was to look for selection rules, or limitations on a particle's behavior imposed by the need to conserve a certain quantity. The conserved quantity was then usually referred to as a quantum number. Instead of seeking selection rules that were always satisfied, Pais decided to look for rules that applied only in certain cases or for certain forces. "Thus I looked for selection rules which would hold for strong and electromagnetic but not for weak processes" (1986, p. 518). He wrote, "The search for ordering principles at this moment may ultimately have to be likened to a chemist's attempt to build up the periodic system if he were only given a dozen odd elements" (1952,1). This insight, which expanded and transformed the notion of a selection rule, "marks the birth of theoretical particle physics" (1997, p. 292).

In 1951 Pais found such a principle: that "the new particles interact strongly only when pairs of them are involved, but weakly when interacting alone" (1997, p. 293). An implication was that strange particles came in pairs, a phenomenon known as "associated production." The experimental case was weak, and several colleagues told him he was simply wrong. Still, Pais described his idea at the institute and at the second Rochester conference in 1952, a series of conferences established to institutionalize the spirit of the Shelter Island conference and its two successors. Oppenheimer entitled Pais's talk at the second Rochester conference, "An Ordering Principle for Megalomorphian Zoology." In it Pais presciently observed that physicists may be witnessing "the unfolding of an ordering in which one talks of families of elementary particles rather than of elementary particles themselves" (1997, p. 293). Pais's paper containing this insight appeared in 1952 (1952,1). The idea of associated production was confirmed by the end of the next year with experiments at the Cosmotron (a high-energy accelerator at Brookhaven National Laboratory that was the first machine able to recreate the energies of cosmic rays in huge quantities and in the confines of the laboratory).

After the second Rochester conference, Pais collaborated with Jost in exploring the link between selection rules, symmetries, and group theory, or the mathematical encoding of invariances and symmetries (1952,2). "Now the possibility dawned on me to try to give that new rule a group theoretical foundation" (1997, pp. 303-304). One group, known as "isospin," was already known in nuclear physics as applied to protons and neutrons. Pais decided to try to expand that group to look for a bigger one—to look for a "higher symmetry"—that would involve a new quantum number; it would have to hold for strong and electromagnetic interactions but be violated in the weak interaction (1953). This was the first introduction of the concept of a higher symmetry in physics, an expansion of physicists' quest for invariances into a new domain. In the same paper Pais also proposed that "the element of space-time is not a point but it is a manifold," which brought into physics an idea that (unknown to Pais) mathematicians already knew under the name "fibre bundles."

Meanwhile, the theorist Murray Gell-Mann was also toying with applying groups to particle families. Pais and Gell-Mann began sharing papers and collaborating. Their joint scheme implied a new quantum number, but they omitted explicit mention of this in a joint paper they gave in Glasgow in summer 1954 (1955,1). Gell-Mann would first present the idea of a new quantum number, which he called "strangeness," in a 1956 paper.

In the mid-1950s Pais underwent several life changes. In 1953 he took a trip around the world, gaining a new appreciation for the art and literature of several countries he visited. His reading list began to include such authors as Yasunari Kawabata and Yukio Mishima (Japan), Pramoedya Ananta Toer (Indonesia), Naguib Mahfouz (Egypt), J. M. Coetzee (South Africa), Halldór Laxness (Iceland), and William Heinesen (Faeroe Islands). Upon his return, he realized that he found Princeton intellectually stimulating but socially and culturally soulless. In 1954 he got an apartment in Greenwich Village, and then moved back and forth weekly between the cloistered university town, still surrounded by farmland, and the cosmopolitan and more diverse Manhattan. He became a U.S. citizen later than year, and met Lila Atwill, a high-fashion model, whom he married on December 15, 1956. Their son, Joshua, was born in Princeton on June 21, 1958.

By this time, as physicists had learned more about strange particles, the nomenclature had changed. A lighter set of strange or V particles came to be known as K particles, while a heavier set was called "hyperons" and included the lambda. That summer Pais made his own contribution to the nomenclature when he introduced the term "baryon," from the Greek for heavy, to denote both nucleons and hyperons (1955,2), the second of his two coinages in the Oxford English Dictionary.

In the course of preparing their Glasgow presentation Gell-Mann and Pais had come across "one new result which astonished us so much that we did not yet dare to insert it in our report" (1997, p. 335). Late in 1954 Gell-Mann joined Pais at his Greenwich Village apartment and the two finally wrote up the idea, one of the most bizarre phenomena in particle physics, the idea of particle mixing (1955,3). The concept can best be explained nontechnically by analogy to the behavior of polarized light. Horizontally and vertically polarized light behave in the same way—they are symmetrical—but cannot change into one another. But they can be mixed in a way that gives rise to circular polarization, where the polarization plane corkscrews left or right. Light that is produced in horizontally and vertically polarized forms can therefore appear as though it came in two other forms: circularly right polarized and circularly left polarized. These two forms of circularly polarized light are said to be produced by the superposition of horizontally and vertically polarized light. But horizontally and vertically polarized light can equally be produced by the superposition of the two forms of circularly polarized light; each of the two pairs can be described as produced by a superposition of the other. Pais and Gell-Mann had noticed that (using later notation, not their own) two K particles—the K^0 and its antiparticle, the anti-K^0—ought to have the ability to mix with each other in a similar way, producing two final states (again using later notation) with substantially different lifetimes, the K-long or K_l and the K-short or K_s.[7] All four "particles" would thus result from a mixing of one particle and its antiparticle. A particle corresponding to the K_s was already known; an analogue to the K_l was not. It was, a theorist later remarked, "One of the most far reaching ideas ever proposed in elementary particle physics."[8]

Pais became a consultant at Brookhaven National Laboratory, making the long drive out once a week with Columbia theorist Robert Serber. Just before the mixing paper appeared, Pais spoke at Brookhaven about particle mixing. The talk electrified the audience. This was far more than the prediction of yet another particle; it was an effect with no classical analogue, a quantum effect with macroscopic implications. One was the existence of the putative K_l, a prediction that was shortly confirmed at Brookhaven.[9] A second startling implication emerged shortly after Pais's Brookhaven talk, when the experimenter Oreste Piccioni pointed out that passing particles through matter shifts their phase in a way that would affect how the particles mix. Such a phase shift could, as it were, "regenerate" some K_l into K_s and vice versa. The outcome was a paper that described what became known as the Pais-Piccioni regeneration effect (1955,4). Writing about this episode a few years later, Richard Feynman called it "one of the greatest achievements of theoretical physics."[10] Pais called it "certainly the best physics I have done in my whole life." (1997, p. 348; 1986, pp. 522-523).

The 1950s was the glamour decade of particle physics, when fundamental discoveries were frequent and public attention high. Mysteries surrounding the behavior of K particles, however, continued to grow, and culminated in the seemingly far-fetched proposal, by T. D. Lee and C. N. Yang, in 1956, that parity—a symmetry long assumed to be fundamental—was violated in the weak interaction. Parity violation in the weak interaction was indeed experimentally confirmed at the beginning of the next year. It was one of the greatest shocks that the physics community ever experienced. The January 1957 issue of *Fortune* magazine ran an article, "The Magnificent Riddle," with photographs of Pais, Gell-Mann, Lee, and Yang.[11] Rosenfeld wrote, "[I]t was Pais's pioneering endeavor to analyze the invariance properties of elementary particles which gave the initial impetus to the theoretical developments culminating in Lee and Yang's discovery" (quoted in 2000, p. 173).

NEW CHALLENGES, NEW DANGERS

During the 1950s, Pais had become prolific, and in 1958 alone published four papers on symmetry properties of strong interactions. He branched out into different fields, including a collaboration on the behavior of pions, proposing what is now known as the GGLP effect, after the authors' initials (1960,1). He worked on a theory of branching ratios (1960,2).

But the 1960s was a more difficult decade for Pais. His father died in January 1960. He spent part of the year in CERN (European Organization for Nuclear Research.) Though not a mountain climber, he decided to climb Mont Blanc, which he could see out of his office window, and thoroughly enjoyed the ascent. The next year he separated from Lila. He had found himself somewhat bored by her only months after their marriage, and frustrated by her bouts of helplessness. In one of Pais's rare engagements in psychoanalysis—which even to his ears must have sounded a little pat, a little too broken of a symmetry—he described his marriage to her as "an attempt at redemption for the loss of my sister, Annie…Taking care of Lila was an attempt at expiating the guilt I continued to feel for not having done enough for my late sister" (1997, p. 362). In 1962 Pais sold his house in Princeton and moved to Reno for a six-week stay to establish residence for a divorce. While in Reno, he received news that he had been elected to the National Academy of Sciences, "happy news that could not have come at a better moment" (1997, p. 381). Later that year he gave himself another physical challenge: he climbed the Matterhorn.

In 1963 Pais decided to leave the institute. “I am in great danger,” he found himself thinking. “I was about to become too content with myself, and to stop striving toward new goals” (1997, p. 385). Pais was attracted to Rockefeller, where Uhlenbeck had been a faculty member since 1961. Uhlenbeck helped arrange an appointment, and Pais joined in 1964.

His fresh start was beset with new challenges. The discovery of CP violation in the weak interaction—another sacred symmetry—at Brookhaven National Laboratory in the spring of 1964 left Pais “shaken” (1997, p. 391). He soon threw himself into research into a highly promising new group, SU(6). The work on SU(6), the “hottest theoretical topic of 1964,” turned into “the most intense period of my later-life scientific activity” (1997, p. 392). A byproduct of SU(6) was the implication that each species of quark should carry one of three distinct values, later called “colors,” though the significance of this idea was not realized for a decade. “So do incomplete but profound thoughts seep barely noticed into the body of physics” (1997, p. 393).

A few months prior to his 50th birthday, on May 19, 1968, Pais had his only bout of genuine depression. “[I]t is as if one looks at a seabed, all water has receded, one only sees wreckage on the bottom” (1997, p. 404). He saw a doctor, who prescribed Tofranil (imipramine), a standard antidepressant. Two months later, just before his birthday, the feeling evaporated.

MASTERING THE ICEBERG: SCIENCE HISTORIAN

Another quantitative difference between writing a research paper and historical work lies in what is sometimes called the iceberg principle: never write all you know, just show the tip of the iceberg, yet convey—and that is a subtle task—that you are aware of much more that lies beneath the surface. The judicious use of this principle distinguishes hacks from good writers. (1997, p. 429)

Pais writes in *Two Continents* that he "stumbled" onto history of science. Yet much in his background had prepared him for it: his eye for telling detail, his fluency in half a dozen languages, his acquaintance with many physics pioneers—at one point he claimed to know 94 Nobel laureates personally—his lifelong interest in literature and history, and his experience in writing review articles such as one in 1968 for *Physics Today* on 20 years of particle physics.

More significantly Pais had a writer's instinct. He liked "fun" words that tasted strange in his mouth and collected them for the right opportunity; thus readers of his prose regularly encounter words like steganography, onomasticon, aphetic, and inspiriting. Coming across the strange word ventripotent (corpulent), Pais awaited a moment to use it, and was enabled in a description of Pauli. Once, reading Gibbon's autobiography, Pais found the English historian's story of how, as a youth, he fell madly in love with a woman with whom his father refused to let him marry. When he came across the sentence, "I sighed as a lover, I obeyed as a son," its astonishing economy and beauty stunned him into silence for hours. Pais had the depth of a European cultural formation, but the freedom of American culture, and used both to the hilt in complying with the iceberg principle. He wrote with the confidence of a fluent writer, yet took advantage of the outsider's ability to recognize and violate convention. In his books he will abruptly announce he is leaving a subject for another, explore it, then leap back unapologetically; or he will switch confidently into a question and answer format that is, stylistically, a non sequitur. Sometimes he liked descriptions he had penned so much that he recycled them in his writings, more than once. The result is a distinctive and inimitable staccato narrative style that is neither personal reminiscence nor historical inquiry, but combines elements of each.

In his biographical writings Pais displays genuine skill and ingenuity in navigating the difficult path of those who seek to provide both a detailed account of scientific discoveries and a fleshed-out profile of those who made them. He writes in a way that is cavalierly and perhaps even self-consciously unconcerned with mainstream historical research. He adopts the position toward his biographical subjects essentially of an inquisitive but not too probing colleague: someone with a superior understanding of matters relating to technical physics issues as well as a privileged access to the personal thoughts and opinions of mutual associates and friends. Pais used these resources well, for the associates and friends confided in Pais things that they surely would not have told a journalist or even a professional historian. Pais relied heavily on the assets he could acquire by this position, and took advantage of the leeway in balance it offered him.

Shortly after Oppenheimer's death in 1967, many colleagues suggested to Pais that he write a biography of the enigmatic man who had been his boss for 16 years at the institute. Good idea, he'd say, and he collected some documents and conducted some interviews. His large office at Rockefeller began to resemble a cross between a research lab and a museum, with rows and rows of meticulously organized papers and notes and a few historical artifacts, including Einstein's last pipe. But he was too busy with physics research, still too in love with it to even consider retiring.

The "stumble" occurred in 1972, after a journal editor asked him to write a review article about the gauge theory of weak interactions. Pais agreed, and envisioned beginning with a prologue outlining the history of the weak interaction and its pioneers. Realizing that "I did not have the vaguest idea what they had done and why," he began a systematic reading of the primary sources. "All that old stuff was new to me," he wrote, full of "surprises" (1997, p. 426). He asked the editor for a few more months so he could write a short book about the physics history of the decade 1895-1905. As he was still actively engaged in physics research, Pais worked on the manuscript in the evenings. But he got stuck when he came to Einstein's first 1905 paper on relativity, which had its own interesting and lengthy prehistory that was hard to incorporate. "It was a disaster," he wrote, "facts piled one upon another in breathless style" (1997, p. 427).

Fortunately Pais had no trouble shedding this diversion and continuing his physics research. Like other theoretical physicists of the time, Pais was astounded with the continuing fecundity of quantum field theory. In the 1940s and early 1950s it had unexpectedly proven to contain sufficient resources to be renormalized. In the late 1950s and early 1960s it fell into some disfavor among many theorists, but in the 1970s theorists explored different kinds of field theories—most notably, gauge theories and quantum chromodynamics—that held new promises. Pais worked on both, in research that included an ongoing collaboration with Sam Treiman, doing such things as calculating hadronic neutral current processes (1972), and another ongoing collaboration with Howard Georgi on CP violation, gauge fields, and symmetries in gauge fields. "We had a lot of fun getting confused about physics together," Georgi once recalled, "usually trying to understand the deeper meaning of some symmetry or other." Pais's final research paper, coauthored with Georgi and one of his postdocs, was on the role of CP violation in QCD and was published in 1981.

Pais had other distractions. In 1975 he married a French instructor, a Princeton faculty member named Sara, but the relationship did not last. The two separated in 1985, and divorced shortly thereafter. In 1976 Pais was offered, but declined, the directorship of the institute.

In 1979 Pais was awarded the Robert Oppenheimer Memorial Prize "in recognition of his contributions to elementary particle physics." As part of the ceremony he gave a talk on Oppenheimer. Afterward, several members of the audience urged him to publish it, and again he briefly thought about writing something longer on the man, and informally interviewed some of Oppenheimer's friends and compatriots, jotting down key remarks. But Pais was in no rush, and had other projects as well. He was asked to report on Einstein's contributions to quantum physics at an Einstein centennial conference planned at Princeton. "This stimulated the thought: Why not go for the whole enchilada and write a full-fledged biography of Einstein's science and his life?" (1997, p. 427). Pais, now in his 60s, was attracted by this new full-time project.

He was keenly aware that he was shifting to a new continent but approached it in an original way. He sharply divided the nontechnical and technical sections, putting the headings and subheadings of the former in italics to help guide the reader. He presented the Einstein story without psychologizing, characterized the historical and social context, commented on the back story of Einstein's ideas, and went for the jugular of the science. The book (1982) was published to wide acclaim, recognized as setting a new standard in writing history of science. In 1983 it won an American Book Award, giving its author no small pride. He remarked at the ceremony, "[F]or a man whose professional language is mathematics and whose native tongue is Dutch, it is a moving experience to be deemed worthy of the American Book award" (1997, p. 438). The book was translated into 15 languages, and brought him international fame. Pais was thrilled, too, when years later the question, "Which scientist is portrayed in the biography *Subtle is the Lord…?*" was included in the game *Trivial Pursuit.*

In the meantime in 1981 Pais had been named Detlev W. Bronk Professor at Rockefeller. Now having mastered the history of relativity, he returned to his earlier historical project, and expanded it from a decade into almost a century. The result was *Inward Bound* (1986), still the standard source for the history of particle physics in the 20th century.

In the fall of 1985 tinkering with the idea of a biography of Niels Bohr, Pais flew to Copenhagen to attend the festivities surrounding the centenary of Bohr's birth on October 7, 1985. The day before the ceremony, his life took "a most unexpected, marvelous turn," when he met Ida Nicolaisen, an associate professor of anthropology at the University of Copenhagen. The two soon spent all their time together, going back and forth between Copenhagen and New York, and married in March 1990. The couple regularly attended concerts and museums together, but museums often for only a short time. "Good paintings made such an impression on Bram that more than once I saw him tremble all over and we had to leave," Nicolaisen recalled. "He would take in art so absolutely that it would fill him up and he could not take it any longer." Most Saturdays they would go to bookstores to stock up. Pais continued to read at least one novel a week, plus what he called "trash," or suspense novels.

After the Bohr biography (1991), Pais had three well-received history books under his belt, and considered writing about Oppenheimer, this time more seriously. Now he encountered another problem, his own ambivalence toward Oppenheimer. While Einstein and Bohr were "simple and good men," Pais says, Oppenheimer did not belong in that category. He compared his attitude to Oppenheimer to people's reactions to New York City: some people love it, others hate it, neither group understands it. The proper attitude toward Oppenheimer and New York City is a love-hate relation. Pais's reluctance to write about a man about whom he felt deeply ambivalent reveals his strengths as a biographer: he knew he had to love the subject if he were to get it right and devote the needed care to it.

Again Pais shelved the Oppenheimer project. He wrote another book on Einstein, taking advantage of new material and examining the physicist's popular reception (1994). Pais also wrote his autobiography, *A Tale of Two Continents* (1997), which he had begun at Nicolaisen's request. Pais balked initially, but agreed once he realized that he did not need to be the center of the tale, but more like the Greek chorus commenting on events.

By the time that appeared Pais conceived the idea of a book consisting of a series of portraits of scientists he knew—recycling some material—to include Oppenheimer. "That would relieve me of the task of writing a more detailed biography of him" (2006). But when he started to work on the Oppenheimer profile, he quickly realized that it would have to be so long as to imbalance the book. Thus *The Genius of Science: A Portrait Gallery* (2000) appeared without an Oppenheimer chapter, which was finally developing into a book of its own.

By mid-2000 Pais had finished the Oppenheimer manuscript up to the morning of April 12, 1954, the day when the hearing over Oppenheimer's security clearance opened in Washington, D.C. The book remained incomplete at Pais's death, though it was published afterward with supplemental material covering Oppenheimer's life after April 1954 (2006).

In 2005 the American Physical Society, through its Forum on the History of Physics, and the American Institute of Physics, through its center for History of Physics, established the Abraham Pais Prize, to recognize outstanding scholarly achievements in the history of physics.

EVER THE CHILD

I have never been young, yet am still a child (1997, p. 248).

Pais once wrote that he hoped to die on the squash court, to "place a soft drop shot just above the corner of the tin, then keel over" (1997, p. 252). That wish went unfulfilled. In June 2000 he and Nicolaisen went to Holland, where Pais delivered what would be his last public lecture, on Madame Curie. The night of their return Pais suffered a heart attack. For a few weeks it looked as though he had recovered, but complications led to his death on July 28, 2000, at the age of 82.

Services were held on August 4, 2000, in Copenhagen and September 13, 2000, in New York. The Copenhagen service took place in the Frederiksberg Kirke, an old baroque church in the center of Copenhagen, which Pais walked by every morning on his way to the Bohr Institute during those parts of the last 15 years of his life that he spent with Nicolaisen in Denmark, and where he was buried, having retained enough of his tribal instincts to request not to be cremated. The service was performed jointly by the chief rabbi of Copenhagen and a priest in the Danish state church. Musical interludes were by Bach, Mozart, Tchaikovsky, and the Beatles ("Let it Be"). The New York service took place at Rockefeller, with classical music during the service (the slow movement of the Mozart clarinet quintet K. 581) and klezmer music during the reception. Pais's services were as cosmopolitan as his life.

Pais rarely luffed his sails, and was always energetically and confidently under way, both as a scientist and as a human being. A man who loved lofty ideas and dirty limericks, classical and popular music, climbing mountains and creating equations, he loathed contentment and constantly challenged himself. Abraham Pais remains a model of what it means to flourish as a human being, in thought and in life, and on all the continents that human beings create for themselves.

NOTES

1. Pais talks about hiding during the occupation not only in 1997 but also in E. Land-Weber, *To Save a Life: Stories of Holocaust Rescue,* pp. 40-55. Urbana: University of Chicago Press, 2000.
2. N. Bohr. Discussion with Einstein on epistemological problems in atomic physics. In *Albert Einstein: Philosopher-Scientist,* ed. P. Schilpp, pp. 201-241. La Salle, Ill.: Open Court, 1970.
3. F. Dyson to "My Dear Family," Nov. 14, 1948.
4. F. Dyson, e-mail message to author, June 14, 2011.
5. T. Reik. *Jewish Wit.* New York: Gamut Press, 1962.
6. A. J. Seriff, R. B. Leighton, C. Hsiao, E. W. Cowan, and C. D. Anderson. Cloud-chamber observations of the new unstable cosmic-ray particles. *Phys. Rev.* 78(1950):290.
7. R. Crease. *Making Physics: A Biography of Brookhaven National Laboratory (1946-1972),* pp. 228-231. Chicago: University of Chicago Press, 1999.
8. J. Sakurai. *Invariance Principles and Elementary Particles,* p 269. Princeton, N.J.: Princeton University Press, 1964.
9. K. Landé, E. T. Booth, J. Impeduglia, L. M. Lederman, and W. Chinowsky. Observation of long-lived neutral V particles. *Phys. Rev.* 103(1956):1901-1904.
10. R. Feynman. *The Theory of Fundamental Processes,* p. 50. Reading, Mass: W. A. Benjamin, 1961.
11. F. Bello. Physics: The magnificent riddle. *Fortune,* Jan. 1957, pp. 121-125, 130, 134, 136, 141.

SELECTED BIBLIOGRAPHY

1941

Projective Theory of Meson Fields and Electromagnetic Properties of Atomic Nuclei. Amsterdam: Noord Hollandsche Uitgeversmaatsch.

1945

On the theory of the electron and of the nucleon. *Phys. Rev.* 68:227-228.

1946

On the theory of elementary particles. *Verh. Kon. Ned. Akad. Nat.* 19/1:1-91.

1947

With C. Møller. The possible existence of mass spectra of fundamental particles. Physical Society, Great Britain: *Report of an International Conference on Fundamental Particles and Low Temperatures held at the Cavendish Laboratory, 22-27 July 1946*, vol. 1, p. 184.

1948

Developments in the Theory of the Electron. Princeton, N.J.: Princeton University Press.

1951

With R. Jost. On the scattering of a particle by a static potential. *Phys. Rev.* 82:840-851.

1952

[1] Some remarks on the V-particles. *Phys. Rev.* 86:663-672.
[2] With R. Jost. Selection rules imposed by charge conjugation and charge symmetry. *Phys. Rev.* 87:871-875.

1953

Isotopic spin and mass quantization. *Physica* 19:869-887.

1955

[1] With M. Gell-Mann. Theoretical views on the new particles. *Proceedings of the Glasgow Conference on Nuclear and Meson Physics.* Oxford: Pergamon.

[2] *Proceedings of the International Conference on Theoretical Physics Kyoto 1954*, p. 157. Tokyo: Science Council of Japan.

[3] With M. Gell-Mann. Behavior of neutral particles under charge conjugation. *Phys. Rev.* 97:1387.

[4] With O. Piccioni. Note on the decay and absorption of the θ^0. *Phys. Rev.* 100:1487-1488.

1960

[1] With G. Goldhaber, S. Goldhaber, and W. Lee. Influence of Bose-Einstein statistics on the antiproton-proton annihilation. *Phys. Rev.* 120:300-312.

[2] The many π-meson problem. *Ann. Phys.* 9:548-602.

1968

Particles. *Phys. Today* 21:24-28.

1972

With S. B. Treiman. Neutral-current effects in a class of gauge field theories. *Phys. Rev. D* 6:2700-2703.

1981

With H. Georgi and T. Tomaras, θ_{QCD} without instantons. *Phys. Rev. D* 23:469-472.

1982

'Subtle is the Lord…': The Science and the Life of Albert Einstein. New York: Oxford University Press.

1986

Inward Bound: Of Matter and Forces in the Physical World. New York: Oxford University Press.

1991

Niels Bohr's Times in Physics, Philosophy and Polity. New York: Oxford University Press.

1994

Einstein Lived Here. New York: Oxford University Press.

1995

Twentieth Century Physics, eds. A. Pais, B. Pippard, and L. Brown. New York: American Institute of Physics Press.

1997

A Tale of Two Continents: A Physicist's Life in a Turbulent World. Princeton, N.J.: Princeton University Press.

2000

The Genius of Science: A Portrait Gallery. New York: Oxford University Press.

2006

J. Robert Oppenheimer: A Life. (With supplemental material by R. P. Crease.) New York: Oxford University Press.