NATIONAL ACADEMY OF SCIENCES

RODNEY LEE COOL

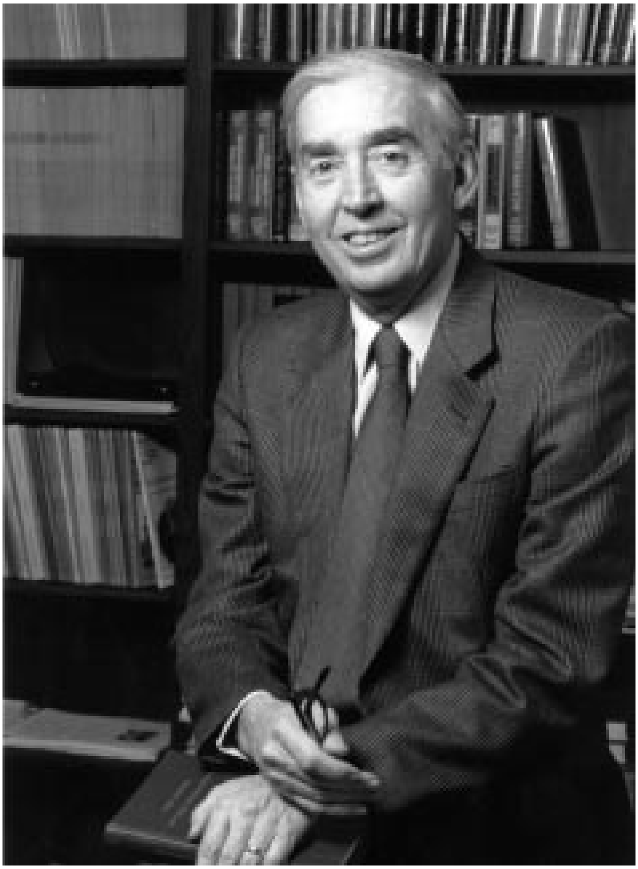
1920—1988

A Biographical Memoir by
ROBERT K. ADAIR

*Any opinions expressed in this memoir are those of the author(s)
and do not necessarily reflect the views of the
National Academy of Sciences.*

Biographical Memoir

COPYRIGHT 1998
NATIONAL ACADEMIES PRESS
WASHINGTON D.C.



Courtesy of the Rockefeller University Archives, New York, New York

Rodney L.

RODNEY LEE COOL

March 8, 1920–April 16, 1988

BY ROBERT K. ADAIR

RODNEY LEE COOL, whose work in experimental elementary particle physics over more than four decades played a significant role in the genesis of that field, was born March 8, 1920, at Platte, South Dakota, to George Edwin and Muriel Post Cool. George Edwin Cool was of Dutch and Norwegian stock. His father anglicized the Dutch name Koel to Cool, which is pronounced the same in the two languages. Muriel, of Dutch and English descent, was born and raised in Connecticut and moved to Platte with her family at the beginning of her high school years.

Platte is about 110 miles west of Sioux Falls and the Minnesota border and 30 miles north of the Nebraska border; about 10 miles to the northwest runs the Missouri River. The town was largely settled in the last decades of the nineteenth century when Cool's grandparents established their homes there. Rod Cool, born only thirty years after South Dakota entered the Union and only thirty years after the tragedy at Wounded Knee when the Indians in the western part of the state were subdued, was very much a son of Hamlin Garland's "middle border." He was raised in the small town with a sister, Harriet Jane, two years younger.

A town of nearly a thousand inhabitants in 1920 and the largest one for 40 miles around, Platte was the commercial center of the wheat growing farms that formed the economic basis of the area. Both of Rodney's parents were schoolteachers. His father, a graduate of Dakota Wesleyan University, earned his four-year degree in education; his mother taught after her graduation from high school in Platte, where she and Rodney's father were the two top students. School teaching was a common and highly respected occupation for educated young women before marriage, and the high schools of that time provided the requisite education.

Rodney Cool's grandfather and two of his brothers established the mercantile and banking facilities in the town of Platte, which prospered during the first three decades of the century. Hence, when Rod was a boy in the 1920s, his economically comfortable parents, well educated for that time and place, assumed they would send their very bright son east to college when the time came. But, the economic crash in 1929, beginning in the eastern stock markets, didn't take long to hit South Dakota. With the general collapse of the world economy augmented by the decade-long mid-western drought—not less bad in the Dakotas than in Oklahoma—the prosperity of the Cools evaporated along with that of their neighbors. While the decade of the 1930s were hard years in all of America, they were desperately hard years in the Dakotas.

So, when Rod finished high school in 1938, a few months after his eighteenth birthday, there was no money to send him east to school and little enough money to help him to go to school anywhere. But he found work that summer, saved a little money, and with a little help from home, in the fall of 1938 he enrolled at the University of South Dakota in Vermillion in the southeast corner of the state about 120 miles from home (and 30 miles from Canton, South Dakota, where Ernest Lawrence and Merle Tuve lived a generation earlier). Discarding an interest in law kindled as an outstanding debater in high school, Cool majored in mathematics and physics at the small school of about a thousand students.

Working summers, evenings, and weekends at school, Rod earned most of the $450 a year required for his tuition and living at the state school, where tuition and fees were only about $50 a year for a state resident. (Families in Platte were doing well at that time if they had an income of $1,000 a year.) Family members recalled that "Rod worked all of the time." But, in between his jobs he studied enough to be elected to Phi Beta Kappa before graduating in the spring of 1942.

In most of the mid-western state universities at that time two years of elementary ROTC courses (Reserve Officer Training Corps) were required of all male students and those judged to be militarily exceptional were invited to enroll in the senior-level training where graduates were awarded a commission in the Army Reserve. Senior ROTC students were paid a sum that was not insignificant in those difficult times. So, Cool, good at soldiering as in everything else, accepted a position in the senior ROTC and was able to give up a few of his more onerous jobs on the campus.

When war came to the United States in 1941, the nominal obligation of the senior ROTC members to serve in the Army Reserve after graduation changed effectively to active service. Hence, shortly after Cool's graduation in 1942, he entered the Army as a second lieutenant in the Signal Corps. He served for four hard years in the Pacific, where his unit landed, usually under fire, to set up communications on the invasion beaches in the course of MacArthur's island hopping that led from the Solomons to

Okinawa and to the war's end in 1945. An excellent soldier and commanding officer, Cool was discharged in 1946 as a major holding the Bronze Star medal—no sinecure at that time.

After leaving the Army, Rod entered Harvard as a graduate student in physics in 1946. With his communications engineering experience and maturity, Rod was immediately useful in experimental physics and J. Curry Street (elected to the National Academy of Sciences in 1953) was pleased that Rod asked to work with him on his cosmic ray work, which was directed towards the determination of the properties of elementary particles. In 1937, Street with E. C. Stevenson had conducted seminal cloud chamber studies of cosmic ray events that demonstrated conclusively the existence of the meson, a particle of mass intermediate between the proton and electron.

Cool worked first in Cambridge with Street and fellow student Earle Fowler on work that resulted in a publication in 1948 of one of the first clear cloud chamber pictures of a meson (now muon) beta decay. Later, again with Street and Fowler and with Robert Sard and William Fowler (Earle's brother) from Washington University in St. Louis, they set up a cloud chamber at Climax, Colorado, where they measured the absorption of muons by aluminum, noting in a paper published in 1949 that the negative muons usually emitted a proton upon absorption.

At 3,410 meters above sea level, Climax, along with Pikes Peak at 4,300 meters and Berthoud Pass at 3,500 meters, all in Colorado, were important centers of cosmic ray work directed in those years primarily towards the determination of the properties of the intermediate mass particles (now pions and muons) produced in the interaction of the high-energy cosmic ray particles—largely protons. As a consequence of the large molybdenum mining operation at

Climax, there was a good road to a high altitude point on the mountain and power was available—even as there was a road and available power at Pike's Peak and at Berthoud Pass.

In the summer of 1948 with his father dead, Rod as the senior member of his branch of the family accepted an obligation to travel to Ketchikan, Alaska, to help settle the estate of his aunt after her husband's death. There he met Margaret MacMillan. In that small town the MacMillans, who had long lived in Alaska (Margaret's mother, Ellen Rogers MacMillan, had taught school in Skagway, where she was born in the gold rush days), were friends of Rod's relatives.

In June 1949 after receiving his Ph.D. from Harvard, Rod and Margaret were married in Ketchikan. After spending the early summer in the Canadian Rockies, where they hiked the trails about beautiful Moraine Lake (shown on Canadian $20 bills circa 1970) from their comfortable cabin on the lake, the couple drove east to Brookhaven National Laboratory—stopping, of course, in South Dakota, where family and friends awaited them.

In the spring before he received his degree, Cool had talked with I. I. Rabi about joining the junior faculty at Columbia. But, teaching undergraduates did not appeal to Rod—although he was an excellent speaker and always at ease on the platform. He also talked with Oreste Piccioni, a few years older than Rodney Cool, who had joined the new Brookhaven Laboratory after conducting a remarkable experiment (with Conversi and Pancini) in wartime Italy which showed that the observed "mesons" (e.g., by Street and Stevenson) were not strongly interacting—and, hence, were not Yukawa's mesons (but the muons we know today.) Piccioni was looking for a colleague to work with him on experiments at the new accelerator, the Cosmotron, the very-high-energy proton synchrotron, then under construction at Brookhaven. Rod found the prospect of working with Oreste—an enthusiastic, exciting, and strikingly original person—to be attractive, and he accepted the position at Brookhaven.

After Rodney and Margaret arrived at Brookhaven on August 1, 1949, Rod learned that the cosmotron was not expected to be ready for two years. Therefore, it was decided that Brookhaven would build a log cabin laboratory at 11,000 feet, just below the 11,500 foot summit of Berthoud Pass, where he and Oreste Piccioni would carry on cosmic ray research using cloud chamber techniques familiar to Rod from his thesis work at Climax.

In January 1950 the five men in the group and their wives left for Georgetown, Colorado, a silver mining ghost town of about 500 people near Berthoud Pass, 50 miles from Denver. Here the five families moved into the only apartments in town, above the bar and post office. It was during their stay in Georgetown that the Cools' two older children Ellen and John were born, with Rod driving their mother through snowstorms to the maternity ward in a Denver hospital.

At Colorado Cool and Piccioni used an iron electromagnet and Geiger counter hodoscopes to examine pion production by protons, which they described in a paper published in 1952. This experiment with Piccioni was the first of a seven-year partnership that generated pioneering measurements of pion interactions using the Brookhaven National Laboratory cosmotron, which came on line late in 1951.

When the cosmotron—soon to accelerate protons to an energy of 3 GeV—was near completion, Rod and Margaret and the two children moved to Long Island near the Brookhaven laboratory where Rod and Oreste began designing the experiments they planned to conduct using the Cosmotron, which was then and for some time to come the world's highest energy accelerator.

At Brookhaven with his proven administrative ability as a field-grade officer in the army and with strong recommendations from Street, Cool was appointed by Sam Goudsmit to the position of assistant physics department chairman (and research physicist) under the department chairman, cosmic ray physicist Tom Johnson. This was the first of the ever-more-important administrative positions that Cool held at Brookhaven, which set much of the general administrative form of high-energy physics there and elsewhere.

When the Cosmotron began running in 1952, providing 10^{10} protons every 5 seconds at the unprecedented energy of 2.2 GeV, Cool and Piccioni, working with Leon Madansky from Johns Hopkins, transferred their efforts to the new accelerator and began an important series of measurements of pion-nucleon total cross sections that did much to establish the complexity of the pion-nucleon interaction. They concentrated on measurements at pion energies greater than 450 MeV while Sam Lindenbaum and Luke Yuan worked at the lower energies to complete the investigations of Fermi and his colleagues at the University of Chicago cyclotron. These investigations had shown a sharp increase in the pion-nucleon scattering and charge-exchange interactions up to energies of about 150 MeV.

The pions were produced by the interaction of the protons with an internal target where pions produced at small angles were then deflected out of the machine by the accelerator magnets to be transported by further magnets to make up a meson beam beyond the accelerator shielding. In this way negative pion beams could be produced up to energies of about 1.5 GeV as the magnetic field that bent the proton beam towards the center of the machine served naturally to eject negative particles. The internal magnetic fields were less fitted to eject positive pions, but reasonable intensities of π^+ mesons in an external beam were achieved up to energies of 1.0 GeV.

Using these beams, Cool, Piccioni, and Madansky—later with David Clark—completed a series of pion-nucleon total cross sections over the accessible energy ranges using fast coincidence circuitry they had developed. In their early experiments they used carbon and hydrocarbon targets to determine proton cross sections through subtraction and water and heavy water targets to determine the deuteron-proton cross section differences, allowing a good estimate of the pion-nucleon cross sections. After 1954 they used liquid hydrogen targets developed at Brookhaven to determine the proton cross sections.

The restriction to internal proton beams at the Cosmotron especially constrained measurements with positive particles, which could be extracted only if they were produced at large angles from targets in the short straight sections of the machine. Since the fluxes of high-momentum particles produced at large angles is necessarily small, this technique severely limited studies of the interaction of high-energy positive particles. Piccioni and Cool with Clark, radio-chemist Gerhart Friedlander, and engineer Dave Kassner developed a scheme for ejecting nearly the whole of the primary proton beam as a well defined external beam. With that beam applied to external targets high-energy positive pion beams were developed and used to extend both the π^+ and π^- cross sections to 1.9 GeV.

Their early measurements at discrete energies of 1.0 and 1.5 GeV showed that the cross sections did not simply vary monotonically with energy and the set of measurements from three years of work presented in an important summary paper published in 1956 showed significant structure. The results of measurements of the whole set of π^+p, π^+n, π^-p, and π^-n cross sections from 450 MeV to 1.5 GeV listed in that paper allowed an interpretation in terms of cross sections for the more fundamental states of definite I-spin, I=1/2, and I=3/2. Moreover, the magnitude of the total cross sections showed that states of high total angular momentum, J, were involved. While taken alone, the I=3/2, J=3/2 enhanced cross section found by Fermi, which was firmly established as a resonance by Lindenbaum and Yuan, might have been considered as just a singular kinematic effect of a strong attractive interaction in that state, the existence of much more complex structure at higher energies in both the I=3/2 and I=1/2 states demonstrated clearly deep inadequacies in the simple pion-nucleon models that had been proposed. Later, extensions of this work led to the spectral information that formed the basis of the quark model of baryon and meson states.

When the Cosmotron, plagued by fatigue failures in its copper bar magnet windings, was scheduled for a year-long repair in 1957, Rod took a year's leave and moved to Berkeley, along with Margaret and children Ellen, John, and now Mary Lee. At the invitation of Ed Lofgren (extended to those Brookhaven physicists who had become under-employed by the Cosmotron shut-down), Rod planned to work at the Lawrence Radiation Laboratory Bevatron, a 6-GeV accelerator that had been running for two years.

At Berkeley, initially working with Bruce Cork and Bill Wenzel and then with Jim Cronin, who had joined Rod at Brookhaven after receiving his degree at Chicago, Cool did the first of a series of measurements that led him into a new research direction. Previous bubble chamber work had shown that the hyperon decay, $\Lambda \rightarrow p + \pi^-$ violated parity inasmuch as the pion was ejected preferentially in the direction of polarization of the lambda. With his colleagues Cool observed sigma decays produced by 1.0 GeV/c π^- mesons interacting with protons. They measured the product, αP, where α is the decay asymmetry of polarized hyperons and P is the degree of polarization generated in the production process. There results showed that the decay $\Sigma^+ \rightarrow p + \pi^0$ displayed a decay asymmetry, α, similar to that of the lambda, while the decay $\Sigma^+ \rightarrow n + \pi^+$ did not, thus demonstrating that P was large, and that the parity violating decay asymmetry depended strongly on the I-spin of the final state. This experiment marked the first work Cool had done pertaining to the weak interactions, rather than the strong interactions, since his work with cosmic rays.

A second experiment at Berkeley by the same group plus Leroy Kerth working with hyperons produced by the interaction of 1.00 GeV/c π^+ mesons on hydrogen led to improved accuracy in the sigma measurements and showed that P (and αP) was large for lambdas.

Back at Brookhaven with the cosmotron now running well and armed with the information that lambdas produced by 1.0 GeV/c π^+ on protons were strongly polarized, Cool with Jenkins, Kycia, Hill, Marshall, and Schluter made the first measurements of the magnetic moment of a hyperon. For technical reasons they preferred to work with charged particle products and hence the reaction, $\pi^+ + n \rightarrow \Lambda^0 + K^+$. By precessing the lambda over its decay path through a strong magnetic field and measuring its decay asymmetry as a function of that field strength, they measured a magnetic moment of -1.5 ±0.5 Bohr nucleon magnetons. The value was a little large (the present value is 0.614±0.005), but the technique was established and the sign of the moment and general magnitude was clearly determined.

A few years later Cool with others measured the magnetic moments of the Ξ^- hyperon, helping to complete the measurements of the moments of the members of the SU3 octet (which include the neutron and proton). The pattern of hyperon magnetic moments set by the measurements showed simplicities that fit the quark model and, hence, helped establish the validity of that model and the reality of quarks.

This remarkable set of experiments setting the magnetic moments of the hyperons, together with the earlier meson cross section measurements, were cited specifically in connection with Rodney Cool's election to the National Academy of Sciences in 1972.

The advent of the large accelerators at Brookhaven and the Lawrence Radiation Laboratory led to new ways of doing physics, and with the new procedures came unprecedented problems concerned with the sharing of resources. For the most part, physicists had worked in the general scientific tradition of individual effort and responsibility. By and large, even as the individual physicist chose the problems he would investigate, he also constructed and operated the equipment that he used to attack these problems.

However, beginning in the middle 1930s with the construction of relatively large cyclotrons and electrostatic generators, nuclear physics had moved into a state where the effort required to build and operate a facility was sufficiently great that the cooperation of groups of physicists was necessary. While the American democratic tradition of governance usually held in form, there was generally a *primus inter pares* at these laboratories, such as Ernest Lawrence at Berkeley. However, there was no such figure among the experimentalists at Brookhaven—or at Berkeley after Lawrence's death in 1956—and with the set of ambitious, strong minded, relatively young physicists competing for the scarce resource of access to these very large accelerators, serious problems of governance arose. Moreover, with the responsibilities of construction and operation of the accelerators largely separated from the responsibilities of the design and operation of experimental programs, the leavening of shared responsibility for the whole facility was reduced. A possibly apocryphal story attributed to Berkeley, but equally applicable to Brookhaven, concerned a conversation after a stormy meeting addressing the scheduling on the accelerator. Someone was supposed to have commented, "What we need is an experienced psychiatrist." Someone else answered, "Hell no! What we need is an experienced kindergarten teacher."

On the small committees developed at Brookhaven in the early 1950s to advise cosmotron department head George Collins on the scheduling of experiments, Rod Cool was always a sensible and conciliatory calm point in the often stormy deliberations. Consequently, laboratory director Leland Hayworth and physics department chairman Sam Goudsmit constructed mechanisms to place Cool at the wheel of the whole experimental program. In 1960 Cool was appointed chairman of high-energy physics, in 1964 assistant director for high-energy physics, and in 1966 associate director of high-energy physics. During this decade Cool served as chairman of an advisory committee that selected the experiments to run on the 30-GeV AGS accelerator—finished in 1957 and again the largest in the world—from proposals by groups of experimenters and set the running schedules.

With his own strong vision of the laboratory, his hard work that led to a command of the details of the many proposals, and his tact and sense of the practical and possible, Cool put his own imprint on the very successful accelerator program at Brookhaven. Moreover, by setting smoothly working procedures in the positions he held and partially created, he set the accelerator governance form at the laboratory that was used with little change in the more than two decades after he left Brookhaven in 1970. At that time he accepted the newly established position of professor of high-energy physics at Rockefeller University.

Cool took a year's sabbatical leave to CERN in the summer of 1962, living in Geneva with Margaret and the children—and new baby Adrienne (who later followed her father in science and is in 1977 an assistant professor of astronomy in the physics and astronomy department at San Francisco State University.) At CERN he worked on the experimental program at the PS accelerator, nearly a twin of the 30-GeV AGS accelerator at Brookhaven, and renewed old friendships with the French physicists from the Ecole Polytechnic, who had worked as students in Colorado on cosmic ray experiments at the same time as Rod in the late 1940s. Rod, Margaret, and the family were to return to Geneva again for a year in 1968-69 and after Cool left Brookhaven for Rockefeller University in the fall of 1970 he worked primarily at CERN, where he and Margaret kept an apartment in Ferney-Voltaire, France, five minutes from CERN. Over the next two decades Rod and Margaret spent about half of their time in their French apartment and about half in their apartment near Rockefeller University in New York.

When Cool joined Rockefeller, his old antipathy to the classroom teaching of elementary physics to undergraduates was not tested, as Rockefeller admitted only graduate students. And after twenty years of increasingly high-level administration at Brookhaven, where he had helped mold the laboratory and set a pattern for high-energy physics administration everywhere, Rod, now fifty years old, never again held an onerous administrative position; he had paid his dues and more, and from then on he would concentrate on the physics he liked best.

Beginning in the summers of the 1950s Rod Cool would spend occasional evenings at moderate-stake poker games with visiting physicists. Sometimes the games were continued at hotel rooms during physics conferences in the United States and abroad. With his wartime training of poker played with fellow officers in the Signal Corps, Rod held his own and more. More important, the poker led to long-time collaborations with fellow players John Tinlot of Rochester and Leon Lederman then at Columbia.

With Tinlot, Lederman, and others, Cool played a major role in measurements of muon proton scattering at high momentum transfers. Then—and to a lesser extent now—the question "Is the muon just a heavier electron?" was unanswered. The most important result of the experiment was that at rather high momentum transfers and correspondingly small distances the muon did just act as a heavy electron. Although then and now the difference in mass was not understood. Also, the electron-proton scattering measurements that probed the electromagnetic structure of the proton and were used by Friedman, Kendall, and Taylor to demonstrate that nucleons had "hard" constituents (i.e., quarks), albeit invaluable, were marred to some extent by the necessity of large corrections for the radiation of the electrons upon collision. While the fluxes of muons were much inferior to the electron currents available, the muons radiated less by a factor of about 40,000 enabling analyses that were superior in some ways.

After going to Rockefeller, Cool assembled an excellent group of younger physicists and with these colleagues Rod moved his efforts again to the world's highest energy accelerator newly built at Fermilab, 30 miles west of Chicago, which accelerated protons to 400 GeV. His work there largely concerned essays into the character of the small angle scattering of protons on protons and neutrons. Some very interesting attempts to find simple ways of understanding the complexities of the physics of elementary particles had centered on the analytic character of particle-particle scattering amplitudes. In particular, the amplitudes that determined the forward scattering of protons by protons and neutrons were considered to be governed by causal dispersion relations similar to the Kramers-Kronig relations that held for the scattering of electromagnetic radiation.

If the results of the program were disappointing in that no surprises emerged, the agreement with the consequences of simple causality generated confidence in the validity of causality and special relativity at small distances, a constraint that remains basic to the important particle theories we have today.

During the decades Cool worked on the physics of elementary particles, the complexities of experiments increased greatly. Along with that increased complexity came increased monetary costs and, sociologically most important, a significant increase in the scientific effort required to conduct an experiment. While Rod's early experiments involved two, three, and four scientists with a few technicians, and typically one or two scientist-years of effort, there are sixteen names on the first Fermilab paper, including seven from the Soviet Union, and those names represent perhaps twenty-five scientist-years of effort. Some of the later CERN papers list thirty names that again represented a very large effort. With so many participants in experiments that are so complex the organization of effort is important and that organization and leadership can only be exercised by a physicist who is knowledgeable about all details of the experiment and has the trust and confidence of everyone. Rodney Cool was often singular in his broad knowledge of the experiment and in how he held the confidence of his colleagues.

Soon after going to Rockefeller Cool also began programs at the CERN intersecting storage ring (ISR), where head-on collisions of 25-GeV protons generated center-of-mass energies that were appreciably higher even than the energies reached at Fermilab—although with a much lower intensity than at Fermilab. Here, he worked mainly on problems connected with the highest momentum transfers—and correspondingly the smallest interaction distances.

Among the high-momentum transfer experiments, Cool worked with Lederman on studies of electron pairs emitted with large invariant masses in the very-high-energy ISR collisions. While they missed (barely) the discovery of the J/ψ particle found independently by Ting and his colleagues at Brookhaven and by Richter and colleagues at SLAC, they confirmed those discoveries almost immediately. But, the very large flux of high transverse momentum π^0 mesons that obscured the J/ψ was in itself a major discovery, proving that the partons seen in deep inelastic scattering were strongly interacting and thus the quarks of quantum chromodynamics.

The effective interaction between quarks is weak at small distances (asymptotic freedom) and strong at large differences—so strong that quarks cannot be separated from their combinations and free quarks are not observed. Consequently, the basic interactions of elementary particles at very small distances (and correspondingly high momentum transfers) can be understood through perturbative calculations, while the interactions at larger distances (and smaller momentum transfers) are relatively intractable. However, among the products of the small-distance, high-momentum-transfer collisions of quarks and electrons with quarks are "jets" of particles where the character of the jets is determined by quark-quark interactions at larger distances. Hence, to extract the character of the fundamental small-distance collision from the experimental data, it is necessary to understand the phenomenology of the jets generated by the collisions.

Much of the rest of Cool's career was spent on high-momentum transfer experiments at CERN, where, through a large number of elegantly designed experiments, Cool and his colleagues managed to construct both the phenomenology of the jets they saw and the character of the fundamental interactions that produced the jets. The analyses of those fundamental collisions provided tests and verifications of quantum chromodynamics in the perturbative region and then played an important role in establishing the validity of that *Standard Model* description of elementary particles.

From his first experiment concerning the beta decay of "light mesons," which we now know as muons, published in 1948 to his last papers published forty years later, Rodney Cool was fortunate enough to live through the intellectual explosion that drove elementary particle physics from its birth up to the significant level of maturity we see today. We who also followed that path are fortunate to have known Rod, who contributed so much to that explosion.

At the time of his death, Cool's survivors included his wife Margaret MacMillin Cool-Dole; daughters Ellen Cool Kwait, Mary Lee Gupta, and Adrienne Margaret Cool; son John Post Cool; and seven grandchildren.

IN WRITING THIS MEMOIR I drew extensively on the generous help of Mrs. Margaret MacMillin Cool-Dole, especially in the recounting of the personal side of Rodney Cool's life. Michael Tannenbaum and Leon Lederman, Cool's collaborators in much of his later work, helped greatly in putting that work in proper perspective.

SELECTED BIBLIOGRAPHY

1948

With E. C. Fowler and J. C. Street. Example of the beta-decay of the light meson. *Phys. Rev.* 74:101.

1949

With E. C. Fowler, J. C. Street, W. B. Fowler and R. D. Sard. Cloud chamber study of mesons stopping in aluminum foils. *Phys. Rev.* 75:1275-76.

1952

With O. Piccioni. Interaction of pions originating in penetrating showers. *Phys. Rev.* 87:531-33.

1954

With L. Madansky, and O. Piccioni. Total cross sections of pions at 1.5 BeV. *Phys. Rev.* 93:249.

1955

With O. Piccioni, D. Clark, G. Friedlander, and D. Kassner. External proton beam of the Cosmotron. *Rev. Sci. Instrum.* 26:232.

1956

With O. Piccioni, and D. Clark. Pion-proton total cross sections from 0.45 to 1.9 Bev. *Phys. Rev.* 103:1082.

1959

With B. Cork, J. W. Cronin and W. A. Wenzel. Asymmetry in the decay of Σ hyperons. *Phys. Rev.* 114:912-20.

1960

With B. Cork, L. Kerth, W. A. Wenzel, and J. W. Cronin. Decay asymmetry of Σ^+ and Λ^0 hyperons. *Phys. Rev.* 120:1000-1004.

1962

With E. W. Jenkins, T. F. Kycia, D. A. Hill, L. Marshall and R. A. Schluter. Measurement of the magnetic moment of the Λ^0 hyperon. *Phys. Rev.* 127:2223-30.

1966

With others. Muon-proton scattering at high momentum transfers. *Phys. Rev. Lett.* 14:724-28.

With G. Giacomelli, T. F. Kycia, B. A. Leontic, K. K. Li, A. Lundby, and J. Teiger. New Structure in the K^--p and K^--d total cross sections between 1.0 and 2.45 GeV/c. *Phys. Rev. Lett.* 16:1228-32.

1967

With R. J. Abrams, G. Giacomelli, T. F. Kycia, B. A. Leontic, K. K. Li, and D. N. Michael. Structure in the $p^{\cdot}$ p and $p^{\cdot}$ n total cross sections between 1.0 and 3.3 GeV/c. *Phys. Rev. Lett.* 18:1209-12.

1972

With G. Giacomelli, E. W. Jenkins, T. F. Kycia, D. A. Leontic, K. K. Li, and J. Teiger. Measurement of the $\Xi^-\Xi^-$ magnetic moment. *Phys. Rev. Lett.* 29:1630-32.

With others. Small angle elastic proton-proton scattering from 25 to 200 GeV. *Phys. Rev. Lett.* 29:1755-57.

1973

With others. Real part of the proton-proton forward-scattering amplitude from 50 to 400 GeV. *Phys. Rev. Lett.* 31:1367-70.

With others. Observation of π^0 mesons with large transverse momentum in high-energy proton-proton collisions. *Phys. Lett. B* 46:471-76.

1974

With others. A search for electron pairs at the CERN ISR. *Phys. Lett. B* 48:377-80.

1975

With others. Diffraction dissociation of high energy protons in p-d interactions. *Phys. Rev. Lett.* 35:766-69.

1976

With others. Total cross sections of $\pi^{\pm}$, $K^{\pm}$, p and $p^{\cdot}$ on protons and deuterons between 23 and 280 GeV/c. *Phys. Lett. B* 61:303-307.

1982

With others. Determination of the angular and energy dependence of hard constituent scattering from π^0 pair events at the Cern Intersection Storage Rings. *Nucl. Phys. B* 209:284-300.

1983

With others. Observation of jet structure in high transverse energy events at the CERN ISR. *Phys. Lett. B* 126:132-36.

1985

With others. Diffraction dissociation of photons on hydrogen. *Phys. Rev. D* 31:17-23.

1987

With others. A measurement of the inclusive π and η production cross sections at high p_T and pp and p·p collisions at $s^{1/2} = 24.3$ GeV. *Phys. Lett. B* 194:568-72.