RESOURCE LETTER

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This is one of a series of Resource Letters on different topics intended to guide college physicists, astronomers, and other scientists to some of the literature and other teaching aids that may help improve course content in specified fields. No Resource Letter is meant to be exhaustive and complete; in time there may be more than one letter on some of the main subjects of interest. Comments on these materials as well as suggestions for future topics will be welcomed. Please send such communications to Professor Roger H. Stuewer, Editor, AAPT Resource Letters, School of Physics and Astronomy, 116 Church Street SE, University of Minnesota, Minneapolis, MN 55455.

Resource Letter HEPP-1: History of elementary-particle physics

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This Resource Letter provides a guide to literature on the history of modern elementary-particle physics. Histories that treat developments from the 1930s through the 1980s are focused on and a sampling is included of the historiography covering the period c. 1890–1930, the prehistory of elementary-particle physics as a discipline. Also included are collections of scientific papers, which might be especially valuable to individuals who wish to undertake historical research on particular scientists or subfields of elementary-particle physics. The introduction presents some statistical data and associated references for elementary-particle physics and surveys historiographical approaches and issues that are represented in historical accounts in the bibliography. All references are assigned a rating of E (Elementary), I (Intermediate), or A (Advanced) based on their technical or conceptual difficulty or their appropriateness for a person attempting a graduated study of the history of modern particle physics. That is, items labeled E are suitable for the layman or would be fundamental to a beginning exploration of the history of particle physics, whereas items labeled A are technically demanding (mathematically, historiographically, or philosophically) or would be most appropriate for specialized or advanced examinations of various topics.

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I. INTRODUCTION

A. Particle physics in modern science

In the famous final "query" of his *Opticks* (in English editions after the first), Isaac Newton wrote:

> There are therefore Agents in Nature able to make the Particles of Bodies stick together by very strong Attractions. And it is the Business of experimental Philosophy to find them out... . [T]o derive two or three general Principles of Motion from Phænomena, and afterwards to tell us how the Properties and Actions of all corporeal Things follow from those manifest Principles, would be a very great step in Philosophy, though the Causes of those Principles were not yet discover'd:... Now by the help of these Principles, all material Things seem to have been composed of...hard and solid Particles..., variously associated in the first Creation by the Counsel of an intelligent Agent.

Speculating about and searching for the ultimate indivisibles out of which everything is made and for the fundamental principles or laws which might unify all the various domains of natural phenomena have been prevalent enterprises in western philosophy and science, both before and after the time of Newton—although nature has not always, even at times within the past century, been conceived as "atomistic" or "unified," nor has its proper explanation always been understood to be "compositional" (that is, to entail description of the world's constituent parts and their arrangement and interrelationships). Since the triumph of the Newtonians—and with them the traditional atomism of Leucippus, Democritus, Epicurus, Lucretius, and Gassendi—in 17th- and 18th-century debates over the interpretation of the "mechanical philosophy" of nature, modern science has progressed very far toward discovering the "general principles" governing "the properties and actions of all corporeal things." And the elementary-particle physics of the past two decades has contributed more than the science of the preceding two centuries toward fulfilling Newton's dream of a comprehensive account of nature, an account explaining complex phenomena in terms of the interactions of, or forces between, fundamental constituents, and, in particular, explaining the process by which the entire Universe was built up from particles (now interpreted in a much broader sense than the "solid, massy, hard, impenetrable, moveable" chunks of matter that Newton had in mind) belonging to a small number of basic species.

In 1962, one wit performed a rudimentary but clever analysis of the growth of particle physics in the 20th century ["Populations: Particles and Physicists," Ira M. Freeman, Am. Scientist **50**, 360A–62A (1962)]. First he made a semilog plot of n vs t for the number n of particle species experimentally known at different epochs t. He found the distribution to be nearly linear, with a doubling time of about 11 years—"obviously identical with the sunspot period." Then he made a semilog plot of the increase in the American physicist population with time and discovered that this distribution surprisingly had "the same doubling time as the elementary-particle curve—11 years!" If the two trends continue, he observed, "the number of physicists will always comfortably exceed the number of elementary particles"; but if the particle curve were just 1% steeper, particle species and physicists would become equal in number after about 13 000 years, and "by the year 15,160 each physicist could be granted immortality by having a particle named after him."

The interesting correspondence between the growth rates of particles and physicists has not continued, however. Although elementary-particle physics has no doubt been the most glamorous and elite subfield of modern physics, compared with other subfields it continues to be relatively small in terms of its number of publications and personnel. Reliable scientometric data for the subfield are available only for the past quarter century. According to *Physics Abstracts* (*Science Abstracts, Series A*), while elementary-particle physics nearly doubled its output of publications over the "boom years" 1964–68 (the springtime of the quark–parton model), during the following two decades such rapid growth was not sustained. From 1977 to 1984, the specialty contributed about 6% of the total number of physics publications; by contrast, nuclear physics contributed about 9%, and condensed-matter physics almost 25%. Over the same period, elementary-particle physics produced half as many physics Ph.D.s in American universities as did condensed-matter physics, yet particle physics received over three times as much U.S. federal funding; and government support for the "small" subfield continues to be quite strong, as witnessed, for example, by Congress's allocation of $243 million for the Superconducting Super Collider (SSC) for fiscal year 1991. Geographically, about 30% of the world's particle physics, based on number of publications, is done in the United States, a slightly larger portion in Western Europe, and about 12% and 7% in the USSR and Japan, respectively. For bibliometric and other quantitative data on recent particle physics (1955–), see:

1. **"World Publication Output in Particle Physics,"** Jan Vlachý, Czech. J. Phys. B **32**, 1065–72 (1982). (A)
2. **"Citation Analysis in Particle Physics,"** Jan Vlachý, Czech. J. Phys. B **32**, 1187–94 (1982). (A)
3. **"World Physics Publication Output—Subfield Distributions and Trends,"** Jan Vlachý, Czech. J. Phys. B **35**, 801–4 (1985). (A)
4. **"Statistical Information on Elementary-Particle Physics Research in the United States,"** Appendix C of *Physics Through the 1990s: Elementary-Particle Physics*, National Research Council (U.S.), Elementary-Particle Physics Panel (National Academy Press, Washington, DC, 1986), pp. 209–12. (E)
5. **A Guide to Experimental Elementary Particle Physics Literature (1985–1989),** S. I. Alekhin *et al.* (Lawrence Berkeley Laboratory, University of California, Berkeley, 1990). "[A]n indexed guide to experimental high energy physics literature for the years 1985–1989. No actual [experimental] data are given, but approximately 3500 papers are indexed by Beam/Target/Momentum, Reaction/Momentum (including the final state), Final State Particle, and Ac-

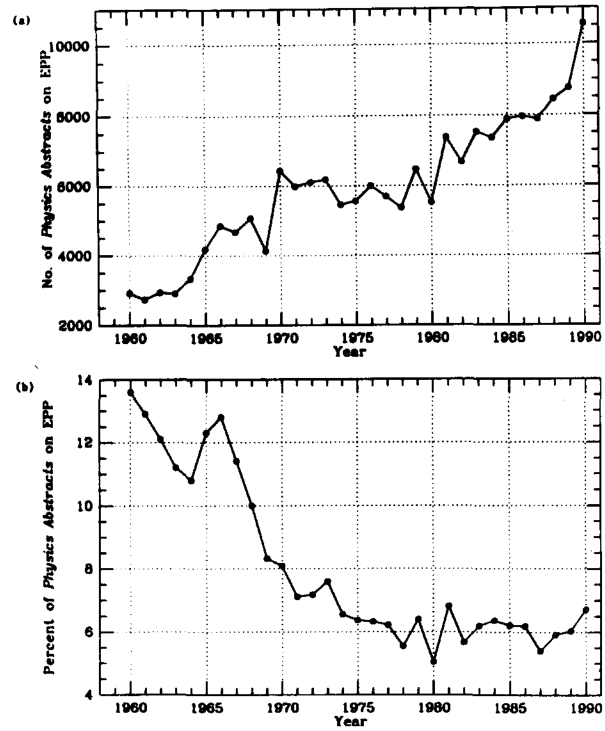

Fig. 1. (a) Annual publication in elementary-particle physics (EPP), as indicated by the number of (numbered) entries in the sections of *Physics Abstracts* devoted to elementary particles, quantum field theory, particle accelerators and detectors and related instrumentation, and cosmic rays. (b) Abstracts on elementary-particle physics as a percentage of all entries in *Physics Abstracts.*

celerator/Experiment/Detector." Includes detailed graphs of the number of experimental papers produced in different countries and laboratories since 1960. (Available from the National Technical Information Service, US Dept. of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.) (A)

6. **"The Growth of the Literature in Physics,"** L. J. Anthony, H. East, and J. Slater, Reports on Progress in Phys. **32**, 709–67 (1969). A general survey of physics publications and physicists' use of literature. (I)

Figures 1–3 present statistics that give some idea of the subfield's recent evolution in terms of publication, personnel, and funding.

B. Historical genres included and omitted

What activities and periods represent "elementary-particle physics"? What constitutes a "historical treatment" of that scientific subfield? In setting temporal and topical boundaries for our historiographical survey—boundaries that are admittedly somewhat arbitrary—we are motivated by our judgment of the areas to which we can do justice in a short bibliography, by our knowledge of the areas already adequately treated in other bibliographies, and by our (subjective—but enlightened, we hope) assessment of the relative importance (to physics and also to history, philosophy, and sociology) of various episodes and components in the history of modern particle physics and of various historiographical approaches to science in general.

Blurredness with regard to what defines elementary-particle physics can arise partly from its historical overlap with the subject matter of other scientific subfields and partly from the evolution of the concept of the "elementary" particle. (Addressing this latter issue, Robert Oppenheimer is said to have supplied what might well be a working definition for the modern physicist: "An 'elementary' particle is something so simple that one knows nothing whatsoever about it.") According to the *Oxford English Dictionary,* the term *elementary particle* (in its modern sense) dates from 1934, *elementary-particle physics* from 1946, and *high-energy physics* from 1962. Yet (as we earlier pointed out) the essential concerns of particle physics go back to ancient times. Here, however, we are interested in the history of elementary-particle physics as a *discipline,* which was born in the early 1930s from an amalgamation of nuclear physics, atomic physics and chemistry, cosmic-ray physics, and quantum field theory. Our historical sketch of that subfield gives preeminence to particle searches and discoveries, while relegating to the periphery the broader area of the physics and chemistry of composite particles (i.e., atomic, molecular, and nuclear physics), which has, in fact, been responsible for many important developments in the physics of elementary particles. While particle physics as a discipline had its beginnings in the 30s, it also has a rich prehistory, which is not generally well known; therefore, we introduce our chronological survey in Sec. VI with a sample of the extensive body of historiography covering the period beginning about 1895.

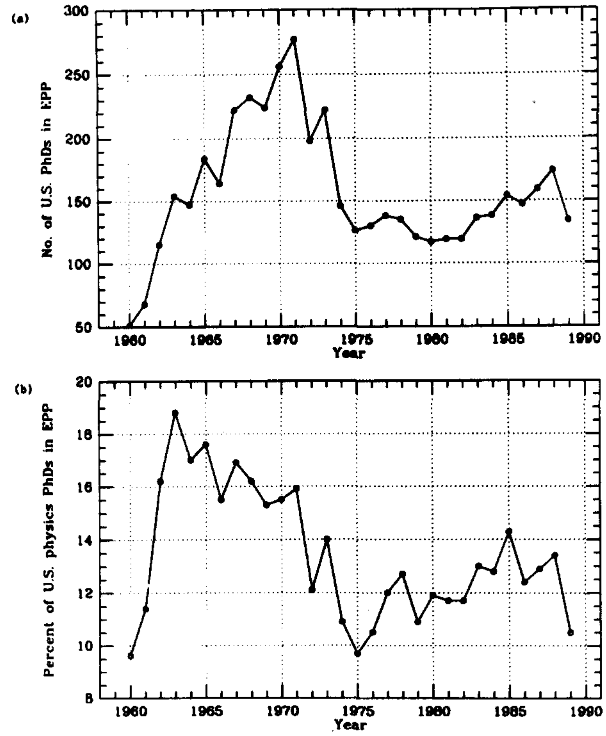

Fig. 2. (a) Number of US doctorates granted in elementary-particle physics. (b) U.S. doctorates granted in elementary-particle physics as a percentage of the total number of US doctorates granted in physics and astronomy. Data are shown for full academic years, where 1960 ≡ academic year 1959–60 = 1 July 1959–30 June 1960, etc. Source: National Research Council doctoral surveys. See also *Physics Through the 1990s: Elementary-Particle Physics* (see Ref. 4), Fig. 8.1 (p. 181), Table C2 (p. 210), and Fig. C2 (p. 211); and *Physics Through the 1990s: An Overview,* NRC, Physics Survey Committee (National Academy Press, Washington, DC, 1986), Fig. S2.1 (p. 93) and Table S2.1 (p. 98).

Distinguished from other Resource Letters, which for the most part have surveyed technical literature of scientific fields (see Sec. II), the present one focuses on *histori-*

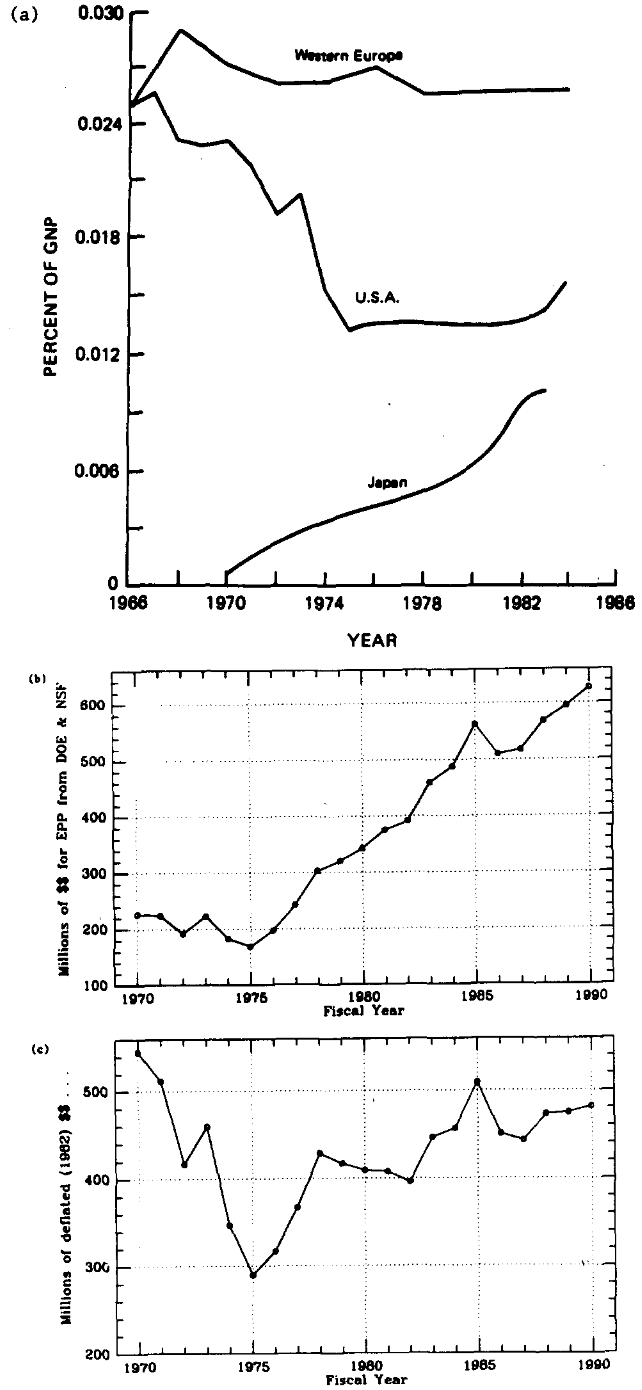

Fig. 3. (a) Funding for elementary-particle physics as a percentage of the gross national product (GNP) for the United States, Japan, and Western Europe. Reprinted with permission from *Physics Through the 1990s: An Overview*, p. 81. (b) U.S. Department of Energy and National Science Foundation funding for elementary-particle physics (in millions of dollars), fiscal years 1970–90. Data include operating, equipment, and construction budgets; SSC funding is excluded. Sources: *Physics Through the 1990s: An Overview*, Table S3.4 (p. 126), and data supplied by the DOE and NSF. (c) Funding from (b) expressed in 1982 (calendar year) constant dollars, using (fiscal year) GNP implicit price deflators. See also *Physics Through the 1990s: Elementary-Particle Physics*, Fig. C3 (p. 212), and *Physics Through the 1990s: An Overview*, Fig. S3.5 (p. 125).

ography. For our purposes, this includes works by professional historians, reminiscences and recollections and other semihistorical accounts by physicists, historical philosophy and sociology of science, and a few pieces of popular science that have a historical orientation.

In our selection we pass over a great number of (but not all) popular and semipopular books and articles about modern physics, which often contain thin historical veins but would prove of little value in constructing a legitimate historical record. In the popular-science genre, we also generally omit some more valuable historical resources, such as articles in *Scientific American*, *Science*, and *Nature*, which often present scientists' firsthand accounts of their work, and the summaries of science news in those journals, which often address the background and significance of new developments. We furthermore exclude most technical treatises and textbooks, which often address (peripherally) the history of their subject but which expressly intend to expound physics proper. At the same time, we recognize that some collections of technical papers, while certainly not qualifying as historiography, might prove valuable for historical research, so we include categories for these. As a final narrowing of the bibliography's breadth, we deal almost exclusively with works in English; Refs. 17 and 18 list many foreign-language resources. It should be noted that our criteria of selection have naturally been relaxed somewhat for more recent developments.

C. The state of the history of elementary-particle physics

Writing the histories of electromagnetism, relativity, and nonrelativistic quantum mechanics has produced cottage industries within the professional history of science. But because high-energy physics only mushroomed in the post-World War II era, historiography of modern particle physics should not reach maturity until the first decade of the next century. Few professional historians have written about particle physics, partly owing to the extensive technical training needed to understand most theoretical and experimental facets of the field. Historically inclined physicists, and scholars interested mainly in social aspects of science, have produced the majority of historical accounts.

Considering the relative youth of many important developments in modern particle physics, the field has been subjected to a surprising variety of historiographical approaches, but few aspects have been given thorough historical analysis, and many potentially fertile topics (for history, philosophy, and sociology) have not been explored at all. The present survey of historiography includes a broad spectrum of analytical possibilities: strictly "internalistic" treatments of the evolution of theories and concepts, and the often associated "scientists' accounts" of a march of ideas and progress; reminiscences encapsulating history in a semibiographical casing; primarily philosophical works evaluating episodes according to the developmental and methodological frameworks of Thomas Kuhn, Imre Lakatos, Karl Popper, Paul Feyerabend, and others; sociological reconstructions and cliometric studies; primarily "externalistic" histories focusing on the scientific community and specific research collaborations; and popularizations concerned mainly with telling an exciting story. In the works surveyed here are various opinions about the "revolutionary" character of events in modern particle physics, the relationship between theory and experiment, the nature of "confirmation," the role of scientists as "passive observers" of nature or as "constructors of phenomena," the sociological interaction of individuals, and the large-scale ideological and social currents within the physics community.

D. Historiographical approaches to science

For those unfamiliar with foci and debates in professional history and philosophy of science, we recommend the following books as introductions to the fields:

7. **An Introduction to the Historiography of Science,** Helge Kragh (Cambridge U. P., New York, 1987). (E)
8. **A Historical Introduction to the Philosophy of Science,** 2nd ed., John Losee (Oxford U. P., New York, 1980). (E)
9. **Philosophy of Science and Historical Enquiry,** John Losee (Clarendon, Oxford, 1987). (I)
10. **The Arch of Knowledge: An Introductory Study of the History of the Philosophy and Methodology of Science,** David Oldroyd (Methuen, New York, 1986). (I)

Several useful, short essays on the historiography of science constitute part of

11. **Companion to the History of Modern Science,** edited by R. C. Olby, G. N. Cantor, J. R. R. Christie, and M. J. S. Hodge (Routledge, New York, 1990). See especially "The Development of the Historiography of Science," John R. R. Christie (pp. 5–22); "The History of Science and the Philosophy of Science," Larry Laudan (pp. 47–59); and "Sociological Theories of Scientific Knowledge," Barry Barnes (pp. 60–73). (E)

Of the historiographical issues that are relevant to understanding and evaluating the works treating the history of modern elementary-particle physics, the most important, in our estimation, are the following:

1. The "scientist's account"

Criticizing the practice of scientists writing history, the American historian Paul Forman once remarked, "[F]or scientists history is not the field upon which they wrestle for truth, but principally their field of celebration and self-congratulation." Perhaps traditionally that has been the case, but not all histories written by scientists are "scientists' histories," nor are such works produced exclusively by scientists. This appellation refers to literature having characteristics often found in accounts given by scientists, accounts which—while claiming to be more than historical sketches or summaries, which by nature cannot accommodate much analysis, synthesis, or critical approach—have tended to lack historical and philosophical awareness and synthesis. The genre typically treats only the great geniuses of successful science and traces the series of names, dates, equations, and important papers marking the triumphant route to contemporary knowledge, and it was once the predominant genre in the history of science. It has been criticized on account of (a) the narrow, misleading picture of history that its works usually present, owing to the actual history that they omit, for example, "unsuccessful" science and the "human context" of scientific activity, including social and cultural influences on and the psychologies of individual scientists; (b) the genre's tendency to detail the "facts" of history and not to establish an interpretive framework for or plausible linkage between them; (c) the genre's tendency to view past science solely through the eyes of current scientific understanding, the sin that has been dubbed "Whig history"; (d) the frequent unreliability of scientists' statements about their own work; and (e) the naïveté of scientists' tendency to view scientific development as cumulative validations of theory by distinct, "closed" experiments—whose data, as "brute facts," present no intrinsic interpretive difficulties—performed on a completely objective world whose phenomena wait to be discovered, probed, and decoded by the unbiased researcher. Although professional history of science in the 20th century compensated for the weaknesses of "scientists' histories," characteristics of that type of literature can be found in a number of works in our bibliography.

2. Theories of scientific development and methodology

The chief expositions of the most popular theories are:

12. **The Logic of Scientific Discovery,** Karl R. Popper (Basic Books, New York, 1959). (I)
13. **The Structure of Scientific Revolutions,** Thomas S. Kuhn (University of Chicago Press, Chicago, 1962; 2nd ed, enlarged, 1970). (I)
14. **The Methodology of Scientific Research Programmes,** Imre Lakatos, edited by John Worrall and Gregory Currie (Cambridge U. P., New York, 1978). (Vol. 1 of Lakatos's *Philosophical Papers.*) (I)
15. **Against Method: Outline of an Anarchistic Theory of Knowledge,** Paul K. Feyerabend (Humanities Press, Atlantic Highlands, NJ, 1975). (I)

According to Popper, the scientific process consists of proposing "conjectures" (hypotheses, theories) and then trying to "falsify," or refute, them through empirical tests. To him the essence of science, as demarcated from non-science, lies in its ability to produce theories that are falsifiable, and different theories are to be weighed on the basis of their power to make predictions that can be tested by direct observation.

Kuhn's theory of scientific development has been the most pervasive in modern philosophical, sociological, and historical analyses of science, although it became generally rejected by philosophers and historians in the 1970s. The chief concepts presented in his famous book were those of (a) the "paradigm," (which Kuhn used in at least 21 different senses, according to one scholar's analysis, but which generally refers to) the network of conceptual, theoretical, and methodological beliefs (or "commitments") that govern a scientific tradition or community at a particular time; (b) the "normal science" that goes on as scientists work at "puzzle-solving" within the paradigm; (c) the period of "crisis," during which a paradigm's fundamental assumptions are questioned, owing to the paradigm's having been overwhelmed with anomalies unexplainable within it; and (d) the "scientific revolution" that subsequently occurs as an older paradigm is replaced wholly or partly by an incompatible, or "incommensurable," new one.

As a synthesis of Popper's and Kuhn's ideas, Lakatos offered his "methodology of scientific research programmes," central to which were the concepts of (a) the "research programme," a set of methodological rules, their practice, and the science that emerges therefrom; (b) the "positive heuristic" and "negative heuristic," components of a research programme that tell a researcher what paths of research to pursue and what paths to avoid, respectively; (c) the "hard core" of a research programme (cf. Kuhn's "paradigm"), that set of fundamental assumptions, hypotheses, and theories which are not subject to alteration or refutation and which are specified by the negative heuristic; (d) the "protective belt" of a research programme, that set of assumptions, hypotheses, and theories which *can* be altered or refuted and which form the substance of the "game" of actual research (cf. Kuhn's "normal science"), in which the suggestions of the positive heuristic are exploited; (e) the "progressive problemshift," which occurs when theoretical work within the protective belt leads to new empirical predictions that are borne out by experiment; and (f) the "degenerating problemshift," which occurs when empirical anomalies must be explained by using *ad hoc* hypotheses that save the hard core but add no new empirical predictions.

As its title indicates, Feyerabend's *Against Method* urged the wholesale abandonment of belief in scientific "method" and scientific rationality. According to his theory of methodological "anarchy" and relativistic knowledge claims, science is merely one knowledge system among many, a product of the cultural and psychological biases of particular communities and individuals.

Despite the contestable tenability of efforts to construct grand schemes describing scientific activity and growth, the theories of Popper, Kuhn, Lakatos, and Feyerabend (or certain features of those theories, at least) have enjoyed a great deal of exploration and influence since their publication. Among scientists, Popper's ideas have had widest acceptance, followed by those of Kuhn (who has been especially popular with physicists), while Lakatos and Feyerabend remain virtually unknown outside professional history and philosophy of science. Demonstrating the limited applicability of these theories has been a major activity within the philosophy and history of science. Kuhn's concepts in particular (along with somewhat similar ideas enunciated by Feyerabend in his less radical writings during the 1960s) have been attacked as being vague and ambiguous, and his approach (despite its professed novel attentiveness to the historical record) has been criticized as being antihistorical, as reconstructing episodes in the history of science to fit his theory of science instead of modeling a theory of science to fit science itself.

3. *The "social construction" of scientific knowledge*

Critics of Kuhn charged that taking seriously two central aspects of his broadly defined "paradigm" concept—(a) the thesis of the "theory-ladenness of observation," according to which all observations of nature are colored by the particular paradigm in which the observer works, and (b) the "incommensurability" thesis, according to which concepts, facts, observations, problems, methods, etc., take on completely different meanings in different paradigms and hence cannot be subject to transparadigmatic comparison—would lead inevitably to a denial of the objectivity and rationality of science and to total relativism with regard to knowledge claims. The seemingly implied picture of science (and the picture later made explicit in Feyerabend's "anything goes" view) as an enterprise shaped in each era by the faddish, collective beliefs (i.e., paradigm) of the community of practitioners and as an enterprise whose "truths" and historical "progress" were nonissues, gave impetus to sociological investigations of the "external" (i.e., sociological, political, cultural, economic, religious, psychological, or other "nonscientific") considerations affecting the activity *and* (more controversially) the *content* of science and, in particular, to investigations of scientific epistemology by "sociologists of knowledge," according to whom conclusions (knowledge, facts) about the world are "socially constructed" through "negotiations" among scientists satisfying various sociological "interests," so that scientific knowledge is relative to different thinkers, communities, cultures, and traditions and is capable of expressing no objective truth.

4. *The "history and philosophy of experiment"*

Only within the past decade has the experimental side of science begun to receive significant attention from historians and philosophers of science. Until the late 1970s, theory was the dominant subject in most analyses, and the discussion of experiment was generally confined to biographies of famous experimenters and to purely descriptive accounts of the classic experiments. But the obsession with theory and the neglect of experiment began to receive reaction from a small number of historians and philosophers of science, including Ian Hacking, Peter Galison, Allan Franklin, and Roger Stuewer; and their work, coupled with sociologists' studies of the social dynamics of experimental science, coalesced into a new school devoted to integrative historical, philosophical, and sociological examinations of experiments and experimental practice. Studies in the "history and philosophy of experiment" have focused on the role of experiments in choosing between or confirming various theories and hypotheses; the constraints (e.g., instrumental availability, economic resources, and experimenters' skills) that influence the choice of experiments and the direction they take; the factors that influence the acceptance or rejection of experimental data, and the encompassing process by which experimental results become elevated to the status of "evidence" or become discarded as "artifacts" of the apparatus; and the social structure of and interactions within teams of experimenters.

5. *Scientometric historiography*

Although scientometrics is primarily the province of sociologists rather than of historians, its techniques have been applied to reach historical conclusions about the growth and distribution of science and about the importance or influence of various scientific developments and contributions. Typically such quantitative analyses are based on counts of scientists, scientific publications, scientific discoveries and inventions, scientific awards, or citations of scientific publications.

Particularly popular in recent years have been the techniques of citation and cocitation analysis. Citation analysis uses the number of times one scientific publication is quoted in other scientific publications to assess the impact of the work, and cocitation analysis uses the number of times different *pairs* of publications are cited in other publications to identify "intellectual foci" of scientific disciplines and also relates such pairs to each other in order to identify the "cognitive kernel" of a specialty. For science since 1961, these analyses are aided by the SCI (*Science Citation Index*), which currently covers systematically the citations in over 3 000 scientific journals and monograph series.

As they have been applied to science, all of the forms of quantitative historiography, or "cliometrics," have displayed certain methodological defects, which render those techniques *alone* of dubious value for giving a reliable picture of the processes at work in the actual development of science, especially during past ages. In particular, the counting of "scientists" and "scientific publications" presupposes an understanding of the nature of science at particular times, and the counting of past scientific "discoveries" assumes that these were temporally localizable, discrete events whose significance was immediately recognized. Furthermore, conclusions based strictly on citation counting assume that scientists systematically and accurately give credit to the work that has influenced their own; whereas in reality cosmetic references adorn many scientific papers, a portion of literature customarily goes unmentioned because its content is "tacit" knowledge assumed to be familiar to all practitioners in a specialty, scientists sometimes deliberately omit references to contributions by their rivals or by pariahs of their discipline, and authors consistently avoid references to works that they plagiarize in part. However, when approached critically and used as a supplement to traditional historiographical methods, scientometrics can be a valuable tool—especially in studies of recent science—for filling in certain dimensions of the historical picture and for enforcing or correcting various historical hypotheses.

II. BIBLIOGRAPHIC AIDS

Several bibliographies serve as valuable supplements to this Resource Letter in covering the history of elementary-particle physics.

16. **The History of Modern Science: A Guide to the Second Scientific Revolution, 1800–1950,** Stephen G. Brush (Iowa State U. P., Ames, 1988). Provides summaries, suggested student readings, and annotated bibliographies for many topics in the history of modern science, including atomic structure, nuclear physics, and particle physics (until 1957). The bibliographies cover mostly recent or particularly important sources. (I)
17. **The History of Modern Physics: An International Bibliography,** Stephen G. Brush and Lanfranco Belloni (Garland, New York, 1983). An extensive, annotated bibliography for the history of physics after 1895. Includes some non-English works, and sections on biographies and collected works, the electron, field theory and quantum electrodynamics, nuclear physics, atomic physics experiments, and elementary particles and high-energy physics. (A)
18. **Literature on the History of Physics in the 20th Century,** J. L. Heilbron and Bruce R. Wheaton (Office for History of Science and Technology, University of California, Berkeley, 1981). An extensive bibliography including a number of non-English works, and sections on biography, atomic physics, nuclear physics, quantum physics, particles and beams, and particle accelerators and detectors. (A)
19. **Bibliography,** Appendix 3 of *Particle Physics: The Quest for the Substance of Substance*, L. B. Okun (Harwood, New York, 1985), pp. 179–217. Lists about 600 popular-science articles and review papers published between 1976 and 1982. (I)
20. **"Scientometric Analyses in Physics: A Bibliography of Publication, Citation and Mobility Studies,"** Jan Vlachý, Czech. J. Phys. B 35, 1389–1436 (1985). Lists about 1000 publications dealing with bibliometric and sociological aspects of modern physics. (A)

To update the coverage in the more general references above, one should consult the *Isis Current Bibliography* (formerly the *Isis Critical Bibliography*), an annual review of new publications in the history and philosophy of science; therein is also a sizable list of relevant periodicals and serials (and their common abbreviations).

A number of AAPT Resource Letters present annotated bibliographies that are useful for the historical study of particle physics. Only one has been exclusively devoted to historiography:

21. **"Resource Letter HP-1: History of Physics,"** Stephen G. Brush, Am. J. Phys. **55**, 683–91 (1987). (A)

Other Resource Letters have dealt with technical literature:

22. **"Resource Letter MM-1: Magnetic Monopoles,"** Alfred S. Goldhaber and W. Peter Trower, Am. J. Phys. **58**, 429–39 (1990). (A)
23. **"Resource Letter GI-1: Gauge Invariance,"** T. P. Cheng and Ling-Fong Li, Am. J. Phys. **56**, 586–600 (1988). (A)
24. **"Resource Letter CPP-1: Cosmology and Particle Physics,"** David Lindley, Edward W. Kolb, and David N. Schramm, Am. J. Phys. **56**, 492–501 (1988). (A)
25. **"Resource Letter Q-1: Quarks,"** O. W. Greenberg, Am. J. Phys. **50**, 1074–89 (1982). (A)
26. **"Resource Letter SP-2: Symmetry and Group Theory in Physics,"** Joe Rosen, Am. J. Phys. **49**, 304–19 (1981). (A)
27. **"Resource Letter NP-1: New Particles,"** Jonathan L Rosner, Am. J. Phys. **48**, 90–103 (1980). (A)
28. **"Resource Letter WI-1: Weak Interactions,"** Barry R. Holstein, Am. J. Phys. **45**, 1033–39 (1977). (A)
29. **"Resource Letter TQE-1: Tests of Quantum Electrodynamics,"** Morton M. Sternheim, Am. J. Phys. **40**, 1363–73 (1972). (A)
30. **"Resource Letter PD-1: Particle Detectors,"** W. Peter Trower, Am. J. Phys. **38**, 795–805 (1970). (A)
31. **"Resource Letter Neu-1: History of the Neutrino,"** Leon M. Lederman, Am. J. Phys. **38**, 129–36 (1970). (A)
32. **"Resource Letter SP-1: Symmetry in Physics,"** David Park, Am. J. Phys. **36**, 577–84 (1968). (A)
33. **"Resource Letter CR-1: Cosmic Rays,"** J. R. Winckler and D. F. Hofmann, Am. J. Phys. **35**, 2–12 (1967). (A)
34. **"Resource Letter SAP-1: Subatomic Particles,"** Clifford E. Swartz, Am. J. Phys. **34**, 1079–86 (1966). (A)
35. **"Resource Letter PA-1: Particle Accelerators,"** John P. Blewett, Am. J. Phys. **34**, 742–52 (1966). (A)
36. **"Resource Letter ECAN-1: The Electronic Charge and Avogadro's Number,"** David L. Anderson, Am. J. Phys. **34**, 2–8 (1966). (A)
37. **"Resource Letter NS-1: Nuclear Structure,"** M. A. Preston, Am. J. Phys. **32**, 820–24 (1964). (A)

III. JOURNALS

The following journals are common sites for publication in the history of modern particle physics:
American Journal of Physics,
Archive for History of Exact Sciences,
Centaurus,
Contemporary Physics,
Foundations of Physics,
Fundamenta Scientiae,
Historia Scientiarum (formerly *Japanese Studies in the History of Science*),
Historical Studies in the Physical and Biological Sciences (formerly *Historical Studies in the Physical Sciences*),
Isis,
Physics Today,
Reviews of Modern Physics,
Science,
Social Studies of Science (formerly *Science Studies*),
Studies in History and Philosophy of Science.

IV. COLLECTIONS AND REPRINTS

A. Volumes from symposia and workshops

38. **The Birth of Particle Physics,** edited by Laurie M. Brown and Lillian Hoddeson (Cambridge U. P., New York, 1983). Based on the lectures and discussions of physicists and historians at the International Symposium on the History of Particle Physics, held at Fermilab in May 1980. The 23 articles examine the period 1930–52. (E, I)
39. **Pions to Quarks: Particle Physics in the 1950s,** edited by Laurie M. Brown, Max Dresden, and Lillian Hoddeson (Cambridge U. P., New York, 1989). Based on the lectures and discussions of physicists and historians at the Second International Symposium on the History of Particle Physics, held at Fermilab in May 1985. The 47 articles focus on the period 1947–63. (E, I)
40. **International Colloquium on the History of Particle Physics: Some Discoveries, Concepts, Institutions from the Thirties to the Fifties,**

Journal de Physique (Colloque) **43**, C8 (Dec. 1982). Proceedings of a conference held in Paris in July 1982. Contains 31 articles, most of them brief recollections by physicists, on developments in particle physics from 1930 to 1965. (I, A)

41. **40 Years of Particle Physics,** edited by B. Foster and P. H. Fowler (Adam Hilger, Bristol, 1988). Proceedings of the International Conference to Celebrate the 40th Anniversary of the Discoveries of the π and V particles, held at the University of Bristol in July 1987. Contains physicists' recollections of the discoveries and assessments of their significance, and reprints nine experimental papers from the period 1947–52. (I, A)
42. **History of Twentieth Century Physics,** edited by C. Weiner (Academic, New York, 1977). Proceedings of the International School of Physics "Enrico Fermi," Course 57, held in Varenna, Italy, in July and August 1972. Contains historians' analyses and physicists' recollections. (I, A)
43. **The Physicist's Conception of Nature,** edited by Jagdish Mehra (Reidel, Boston, 1973). Proceedings of a symposium held at the International Centre for Theoretical Physics in Miramare, Italy, in September 1972. Contains physicists' essays discussing the historical development of major concepts in 20th-century physics. (I, A)
44. **Symmetries in Physics (1600–1980),** edited by Manuel G. Doncel, Armin Hermann, Louis Michel, and Abraham Pais (Servei de Publicacions, Universitat Autònoma de Barcelona, Bellaterra, Spain, 1987). Proceedings of the First International Meeting on the History of Scientific Ideas, held in San Feliu de Guixols, Spain, in September 1983. (I, A)
45. **Early History of Cosmic Ray Studies: Personal Reminiscences with Old Photographs,** edited by Yataro Sekido and Harry Elliot (Reidel, Boston, 1985). Based on talks given at the International Conference on Cosmic Rays held in Kyoto in August 1979. Contributors include H. Alfvén, C. D. Anderson, P. Auger, W. Heitler, B. Rossi, D. V. Skobeltzyn, and H. Yukawa. (I, A)
46. **Fifty Years of Weak-Interaction Physics,** edited by A. Bertin, R. A. Ricci, and A. Vitale (Italian Physical Society, Bologna, 1984). Celebrates the 50th anniversary of Fermi's theory of nuclear β decay. Contains technical essays appraising the status of weak interaction physics, and reprints 40 important papers in the field from 1934 to 1984. (A)
47. **50 Years of Weak Interactions,** edited by David Cline and Gail Riedasch (University of Wisconsin, Madison, 1984). Proceedings of the Wingspread Conference held in Racine, Wisconsin, in May and June 1984. Contains mostly physicists' essays, focusing on the history of weak interaction theory and the discovery of the weak neutral current and the W and Z particles. (I, A)
48. **The Restructuring of Physical Sciences in Europe and the United States, 1945–1960,** edited by Michelangelo De Maria, Mario Grilli, and Fabio Sebastiani (World Scientific, Singapore, 1989). Proceedings of a conference held in Rome in September 1988. Contains 41 articles by historians and physicists, analyzing institutional, cultural, political, and technical factors in the growth of post-World War II physics. (I, A)
49. **The Development of the Laboratory: Essays on the Place of Experiment in Industrial Civilization,** edited by Frank A. J. L. James (MacMillan, Hampshire, England, 1989). Based on lectures delivered at a Royal Institution Centre for the History of Science and Technology symposium in September 1986. Includes four essays that address the rise of large high-energy physics laboratories in the postwar period. (I)

Two collections have so far been produced by the Japan–USA Collaboration on Particle Physics in Japan:

50. **Particle Physics in Japan, 1930–1950,** 2 vols., edited by Laurie M. Brown, Michiji Konuma, and Ziro Maki (Research Institute for Fundamental Physics, Kyoto University, Kyoto, 1980). The result of four workshops held in the United States and Japan during 1978 and 1979, constituting the first phase of the Collaboration. (A)
51. **Proceedings of the Japan–USA Collaborative Workshops on the History of Particle Theory in Japan, 1935–1960: Japan–USA Collaboration, Second Phase,** edited by Laurie M. Brown, Rokuo Kawabe, Michiji Konuma, and Ziro Maki (Research Institute for Fundamental Physics, Kyoto University, Kyoto, 1988). Contains chapters on the Tomonaga school, the Yukawa school, and S. Sakata and the Nagoya school. Includes some previously unpublished manuscripts, among which are two by Yukawa on meson theory from 1937. (A)

Other collections of sources for the history of Japanese particle physics are Refs. 64 and 66.

References 170 and 171, proceedings of conferences on the history of nuclear physics, are valuable resources for overlapping topics from the early years of elementary-particle physics.

The lectures delivered by Nobel laureates upon the receipt of their prize are often valuable historical sources. Many Nobel prizes have been awarded for contributions to elementary-particle physics.

52. (a) **Nobel Lectures: Physics, 1922–1941** (Elsevier, New York, 1965); (b) **Nobel Lectures: Physics, 1942–1962** (Elsevier, New York, 1964); (c) **Nobel Lectures: Physics, 1963–1970** (Elsevier, New York, 1972). Lectures, presentation speeches, and short biographies of the laureates. (E, I, A)

B. Festschrifts for physicists

53. **Evolution of Particle Physics: A Volume Dedicated to Edoardo Amaldi in [*sic*] His Sixtieth Birthday,** edited by M. Conversi (Academic, New York, 1970). Includes brief biographical notes on Amaldi and reprints L. Alvarez's 1968 Nobel lecture (Ref. 351). (I, A)
54. **Perspectives in Modern Physics: Essays in Honor of Hans A. Bethe,** edited by R. E. Marshak (Interscience, New York, 1966). Contains physicists' recollections. (A)
55. **A Passion for Physics: Essays in Honor of Geoffrey Chew,** edited by Carleton DeTar, J. Finkelstein, and Chung-I Tan (World Scientific, Singapore, 1985). Based on a symposium held in Berkeley, California in September 1984 to celebrate Chew's 60th birthday. Contains contributions by S. Frautschi, M. L. Goldberger, D. J. Gross, S. Mandelstam, and 23 others, as well as the text of an interview with Chew by F. Capra and a list of Chew's publications. (E, A)
56. **Aspects of Quantum Theory,** edited by Abdus Salam and E. P. Wigner (Cambridge U. P., Cambridge, 1972). Fifteen essays honoring the life and work of P. A. M. Dirac on the occasion of his 70th birthday. (I, A)
57. **Physics Today 42** (2) (Feb. 1989). A special issue dedicated to the late Richard Feynman, with reminiscences by colleagues and friends. (E)
58. **Thirty Years Since Parity Nonconservation: A Symposium for T. D. Lee,** edited by Robert Novick (Birkhäuser, Boston, 1988). Proceedings of a symposium at Columbia University in 1986 in honor of Lee's 60th birthday and the 30th anniversary of the discovery of parity violation. Contains recollections of S. Drell, V. L. Telegdi, C. S. Wu, and others, as well as Lee's own reminiscences. (A)
59. **Five Decades of Weak Interactions,** Ann. N.Y. Acad. Sci. **294** (1977), edited by N. P. Chang. Based on a symposium held in New York in January 1977 to honor the 60th birthday of R. E. Marshak. Contributors include H. A. Bethe, Y. Ne'eman, C. S. Wu, and C. N. Yang. (A)
60. **From SU(3) to Gravity: Festschrift in Honor of Yuval Ne'eman,** edited by Errol Gotsman and Gerald Tauber (Cambridge U. P., New York, 1985). Includes a short biography and Ne'eman's curriculum vitae. (A)
61. **Theoretical Physics in the Twentieth Century: A Memorial Volume to Wolfgang Pauli,** edited by M. Fierz and V. F. Weisskopf (Interscience, New York, 1960). Includes a list of Pauli's publications. (A)
62. **Notes and Records of the Royal Society of London 27** (1) (Aug. 1972). Contains lectures and addresses delivered at the Royal Society's celebration, in October 1971, of the centenary of E. Rutherford's birth. Contributors include N. Feather, H. Massey, and M. Oliphant. (A)
63. **Festi-Val: Festschrift for Val Telegdi,** edited by Klaus Winter (North-Holland, New York, 1988). Based in part on a symposium

held at CERN in July 1987 to celebrate Telegdi's 65th birthday. Includes a biographical note and a list of Telegdi's publications. Contributors include S. Chandrasekhar, M. Gell-Mann, L. Michel, and B. Winstein. (I, A)

64. **Supplement of the Progress of Theoretical Physics 37 & 38** (1966). Festschrift for S. Tomonaga on the occasion of his 60th birthday. Includes a list of his scientific papers. (A)

C. Historical articles

65. **History of Physics,** edited by Spencer R. Weart and Melba Phillips (American Institute of Physics, New York, 1985). Reprints 47 articles from *Physics Today,* including 11 in a section on "Particles and Quanta." (E)

66. **Historia Scientiarum 36** (March 1989). A special issue devoted to the history of particle physics in Japan from 1930 to 1960. (A)

D. Primary sources in physics

The following volumes are aimed at the nonspecialist and would be suitable as sources of scientific readings or commentaries on them for students in courses covering the development of modern physics.

67. **The Experimental Foundations of Particle Physics,** Robert N. Cahn and Gerson Goldhaber (Cambridge U. P., New York, 1989). A commendable description of the development of particle physics, supported by a selection of 98 notable experimental papers. Covers the period 1930–83. (I)

68. **Adventures in Experimental Physics,** 5 vols. (α 1972, β 1972, γ Volume, δ Volume, and ϵ Volume), edited by Bogdan Maglich (World Science Communications, Princeton, NJ, 1972–76). Contains reprints of scientific papers, explanatory physics notes for nonspecialists, and researchers' personal discovery stories for a number of episodes involving "innovative, unconventional, and adventurous experimentation." (E)

69. **Landmark Experiments in Twentieth Century Physics,** George L. Trigg (Crane, Russak, New York, 1975). Includes detailed accounts, with extensive quotation from original sources, of several experiments relevant to elementary-particle physics. (I)

70. **Particles and Forces: At the Heart of Matter,** edited by Richard A. Carrigan, Jr., and W. Peter Trower (Freeman, New York, 1990). Reprints and updates 12 articles from *Scientific American* covering theories, experiments, and experimental tools of contemporary elementary-particle physics. (E)

71. **Particle Physics in the Cosmos,** edited by Richard A. Carrigan, Jr., and W. Peter Trower (Freeman, New York, 1989). Reprints and updates 12 articles from *Scientific American* covering recent cosmology and its links with elementary-particle physics. (E)

72. **The World of the Atom,** 2 vols., edited by Henry A. Boorse and Lloyd Motz (Basic Books, New York, 1966). An anthology of original sources, prefaced by brief historical introductions and biographies of the authors. (See also Ref. 478.) (E)

73. **The World of Physics: A Small Library of the Literature of Physics from Antiquity to the Present,** 3 vols., edited by Jefferson Hane Weaver (Simon and Schuster, New York, 1987). An anthology of original sources, prefaced by brief historical introductions. Volume 2 includes sections for papers dealing with "Quanta," "Symmetry," and "Particles." (E)

Small collections of important technical papers are found in Reprint Books based on AAPT Resource Letters:

74. **Quarks: Selected Reprints,** edited by O. W. Greenberg (American Association of Physics Teachers, Stony Brook, NY, 1986). Reprints Ref. 25 and 22 articles, published between 1964 and 1983, relating to the quark model. (A)

75. **New Particles: Selected Reprints,** edited by Jonathan L. Rosner (American Association of Physics Teachers, Stony Brook, NY, 1981). Reprints Ref. 27 and 25 articles on developments in particle physics since 1974, e.g., the J/ψ and related neutral mesons, charmed particles, the τ and ν_τ, and the Υ family of resonances. (A)

The following volumes are aimed at the specialist and contain reprints of papers in various subfields of particle physics.

76. **Foundations of Nuclear Physics,** edited by Robert T. Beyer (Dover, New York, 1949). Reprints classic papers in nuclear and early particle physics from 1911 to 1935. (A)

77. **Nuclear Forces,** D. M. Brink (Pergamon, New York, 1965). Includes reprints and translations of 14 pioneering papers on nuclear forces from 1932 to 1952. (A)

78. **Energy in Atomic Physics, 1925–1960,** edited by R. Bruce Lindsay (Hutchinson Ross, Stroudsburg, PA, 1983). Reprints 46 papers related to the evolution of the "energy" concept, including 21 papers in sections devoted to nuclear and particle physics and high-energy accelerators. (A)

79. **Das Neutron: Eine Artikelsammlung,** edited by B. M. Kedrov (Akademie-Verlag, Berlin, GDR, 1979). Contains scientists' recollections, a survey of the history of the neutron, and reprints of 13 articles from 1920 to 1940. (A)

80. **The Theory of Beta-Decay,** Charles Strachan (Pergamon, New York, 1969). Includes reprints (and one translation) of nine seminal papers in weak interaction physics from 1933 to 1958. (A)

81. **The Development of Weak Interaction Theory,** edited by P. K. Kabir (Gordon & Breach, New York, 1963). Reprints 39 papers in weak interaction physics from 1934 to 1960. (A)

82. **Cosmic Rays,** A. M. Hillas (Pergamon, New York, 1972). Contains reprints and translations of 16 fundamental papers in cosmic-ray research from 1912 to 1958. (A)

83. **Selected Papers on Quantum Electrodynamics,** edited by Julian Schwinger (Dover, New York, 1958). Reprints 34 important papers, published between 1927 and 1953, by H. A. Bethe, P. A. M. Dirac, F. J. Dyson, R. P. Feynman, W. E. Lamb, J. Schwinger, S. Tomonaga, V. S. Weisskopf, and others. Contains a brief, historical preface by Schwinger. (A)

84. **Quantum Electrodynamics: A Lecture Note and Reprint Volume,** R. P. Feynman (Benjamin, New York,1961). Includes reprints of three of Feynman's seminal papers from 1949 and 1951. (A)

85. **Supplement of the Progress of Theoretical Physics 1** and **2** (1955). No. 1, *Collected Papers on Meson Theory I: Formalism and Models,* contains a short, historical introduction ("Progress in Meson Theory in Japan") by S. Tomonaga and reprints 34 Japanese papers on meson theory from 1935 to 1950. No. 2, *Collected Papers on Meson Theory II: Intermediate and Strong Coupling Theories,* reprints 10 papers, most of them by Tomonaga, from 1941 to 1953. (A)

86. **Complex Angular Momenta and Particle Physics: A Lecture Note and Reprint Volume,** E. J. Squires (Benjamin, New York, 1963). A technical monograph supplemented by reprints of eight papers (1962–63) by G. F. Chew, M. L. Goldberger, S. Mandelstam, and others. (A)

87. **S-Matrix Theory of Strong Interactions: A Lecture Note and Reprint Volume,** Geoffrey F. Chew (Benjamin, New York, 1961). Includes a historical survey by Chew, and reprints six papers (1958–60) by L. D. Landau, S. Mandelstam, T. Regge, and others. (A)

88. **The Eightfold Way,** Murray Gell-Mann and Yuval Ne'eman (Benjamin, New York, 1964). Reprints 30 papers from the period 1961–64, during which the SU(3) symmetry group was extensively explored as a classification scheme for hadrons. (A)

89. **Symmetry Groups in Nuclear and Particle Physics: A Lecture-Note and Reprint Volume,** Freeman J. Dyson (Benjamin, New York, 1966). A sequel to Ref. 88 that reprints 32 papers, most of which deal with the SU(6) group and its generalizations. (A)

90. **The Quark Model,** J. J. J. Kokkedee (Benjamin, New York, 1969). An informal technical monograph supplemented by reprints of 19 early papers on quarks and composite models. (A)

91. **Current Algebras and Applications to Particle Physics,** Stephen L. Adler and Roger F. Dashen (Benjamin, New York, 1968). Reprints 22 important papers, supplemented by an explanatory text, on early applications of the "current algebra" and "partially conserved axial-vector current" hypotheses in the theory of the weak and electromagnetic interactions of hadrons. (A)

92. **Selected Papers on Gauge Theory of Weak and Electromagnetic In-**

teractions, edited by C. H. Lai (World Scientific, Singapore, 1981). Reprints 34 pioneering technical papers from 1954 to 1976, plus the 1979 Nobel lectures of S. L. Glashow, A. Salam, and S. Weinberg (Refs. 376–78). (E, I, A)

93. **Selected Papers on Gauge Theories of Fundamental Interactions,** edited by R. N. Mohapatra and C. H. Lai (World Scientific, Singapore, 1981). A sequel to Ref. 92. Reprints 50 papers from 1964 to 1980. Main topics are the quantization and renormalization of gauge theories, gauge theories of the strong interactions, and GUTs. (A)
94. **Unity of Forces in the Universe,** 2 vols., edited by A. Zee (World Scientific, Singapore, 1982). Reprints 78 papers concerning the unification of the strong, weak, and electromagnetic interactions and the interface between grand unification and cosmology. (A)
95. **Inflationary Cosmology,** L. F. Abbott and So-Young Pi (World Scientific, Singapore, 1986). Reprints 62 papers from 1966 to 1986. Includes the pioneering papers of A. Guth, A. Linde, A. Albrecht, and P. Steinhardt, and includes chapters, with brief introductions, on dark matter, the microwave background, baryon generation, the field-theory background to inflationary cosmology, and other topics. (A)
96. **The Early Universe: Reprints,** edited by Edward W. Kolb and Michael S. Turner (Addison-Wesley, Redwood City, CA, 1988). Reprints 48 papers on primordial nucleosynthesis, baryogenesis, quantum cosmology, and other topics. Complements the coverage of the companion monograph *The Early Universe.* (A)

Collections of reprints are also found in Refs. 41, 46, and 425.

E. Collected works of individual scientists

97. **Discovering Alvarez: Selected Works of Luis W. Alvarez, with Commentary by His Students and Colleagues,** edited by W. Peter Trower (University of Chicago Press, Chicago, 1987). (A)
98. **Enrico Fermi, Collected Papers (Note e memorie),** 2 vols. (University of Chicago Press, Chicago, 1962 and 1965). Volume 1: Italy, 1921–38; Vol. 2: U.S., 1939–54. (A)
99. **T. D. Lee: Selected Papers,** 3 vols., edited by G. Feinberg (Birkhäuser, Boston, 1986). Volume 1 is devoted to "Weak Interactions and Early Papers," Vol. 2 to "Field Theory and Symmetry Principles," and Vol. 3 to discrete physics, strong interaction models, historical papers, and gravity. (A)
100. **Collected Scientific Papers by Wolfgang Pauli,** 2 vols., edited by R. Kronig and V. F. Weisskopf (Interscience, New York, 1964). Volume 1 is devoted to books and contributions to books, and Vol. 2 to journal articles, conference reports, contributions to discussions, and book reviews. (A)
101. **Selected Papers of Cecil Frank Powell,** edited by E. H. S. Burhop, W. O. Lock, and M. G. K. Menon (North-Holland, Amsterdam, 1972). (A)
102. **The Collected Papers of Lord Rutherford of Nelson,** 3 vols., edited by James Chadwick (Interscience, New York, 1962, 1963, and 1965). (A)
103. **Shoichi Sakata: Scientific Works** (Publication Committee of Scientific Papers of Prof. Sakata, Tokyo, 1977). (A)
104. **Selected Papers (1937–1976) of Julian Schwinger,** edited by M. Flato, C. Fronsdal, and K. A. Milton (Reidel, Boston, 1979). (A)
105. **Scientific Papers of Tomonaga,** 2 vols., edited by T. Miyazima (Misuzu Shobo, Tokyo, 1971 and 1976). Volume 1 covers the period 1933–66 and includes Tomonaga's important contributions to particle physics. Volume 2 contains papers on ultra-short wave circuits and magnetrons, review articles and notes from a lecture on elementary-particle physics, and miscellaneous "short sentences." (A)
106. **Selected Papers, 1945–1980, with Commentary,** Chen Ning Yang (Freeman, San Francisco, 1983). (A)
107. **Hideki Yukawa: Scientific Works,** edited by Yasutaka Tanikawa (Iwanami Shoten, Tokyo, 1979). (A)

See also Refs. 204, 487, and 494.

V. TEMPORALLY AND TOPICALLY BROAD SURVEYS

The following works contain overviews and surveys that would be appropriate as readings for students in courses treating the history of elementary-particle physics at various levels of sophistication. Similarly comprehensive in scope are Ref. 475 and the already mentioned collections of historical articles and symposium papers.

A. History-oriented works

108. **Inward Bound: Of Matter and Forces in the Physical World,** Abraham Pais (Oxford U. P., New York, 1986). A monumental volume providing extensive coverage of the history of theoretical and experimental particle physics, 1895–1983. (A)
109. **The Second Creation: Makers of the Revolution in Twentieth-Century Physics,** Robert P. Crease and Charles C. Mann (Macmillan, New York, 1986). An absorbing, biographically structured history of modern particle physics, focusing on the "style" and "personality" that have shaped that "most human of creative practices." Based partly on interviews (with over a hundred scientists), scientists' private papers and correspondence, and the authors' visits to laboratories. (E)
110. **Constructing Quarks: A Sociological History of Particle Physics,** Andrew Pickering (University of Chicago Press, Chicago, 1984). An excellent, detailed history of postwar theoretical and experimental high-energy physics, focusing on the development and extension of the quark model and the Weinberg–Salam electroweak theory. The author's historical account is used to support the contention that scientific knowledge is socially "constructed," and he purports to "explain the dynamics of [scientific] practice in terms of the ['opportunistic'] contexts within which researchers find themselves, and the resources which they have available for the exploitation of those contexts." [See also an informative essay review of the book, "Constraints on Construction," Yves Gingras and Silvan S. Schweber, Soc. Stud. Sci. **16**, 372–83 (1986).] (I)
111. **The Tenth Dimension: An Informal History of High Energy Physics,** Jeremy Bernstein (McGraw-Hill, New York, 1989). An outline, focusing on the past three decades, of "the history and the science of the entire field of elementary-particle physics and cosmology," by a physicist and award-winning science writer. (E)
112. **How Experiments End,** Peter Galison (University of Chicago Press, Chicago, 1987). An engaging treatise devoted to the history, philosophy, and sociology of laboratory science in 20th-century microphysics. Contrasts the performance and interpretation of experiments in three epochs (measurements of atomic gyromagnetic ratio in the 1910s and 1920s, cosmic-ray and radioactivity experiments in the 1920s and 1930s, and high-energy experiments on neutral currents in the 1970s) to illuminate "how arguments emerge from the modern physical laboratory" and how the scale of physics and the interaction between theoretical and experimental work have evolved during this century. (I)
113. **The Neglect of Experiment,** Allan Franklin (Cambridge U. P., New York, 1986). A treatise on the history and philosophy of experiment, based on case studies of the discovery (and nondiscovery) of parity violation, the confirmation of *CP* violation, and the oil drop experiments of Millikan. Contains edited versions of Refs. 316, 318, and 363 and also incorporates significant parts of Refs. 146 and 147. (I)
114. **Experiment, Right or Wrong,** Allan Franklin (Cambridge U. P., New York, 1990). Addresses the role of experiments in theory choice and confirmation and the process by which scientists come to believe rationally in experimental results. Elaborates, in terms of Bayesian confirmation theory, the epistemology of experiment presented in (for example) Ref. 113. Argues that "the history of physics shows that experimental results are both fallible and corrigible," and examines in detail the cases of (1) the interaction between experiment and theory in weak interaction physics from Fermi's theory (1934) to the *V–A* theory (1957) and (2) the interaction between atomic parity violation experiments of the 1970s and 1980s and the Weinberg–Salam electroweak theory. Incorporates a version of Ref. 207. (I)

115. **"Subatomic Particles,"** Christine Sutton, in *Encyclopedia Britannica*, 1990 ed., Vol. 28, pp. 249–63. Provides a historical sketch of the field from 1897 to 1984. (E)
116. **"Particle Science,"** Helge Kragh, in Ref. 11, pp. 661–76. Includes a survey of chemists' speculations in the 19th century. (E)
117. **"Historical Introduction,"** Chap. 1; and **"Note Added in Proof, 3"**; in *Quantum Field Theory*, H. Umezawa (Interscience, New York, 1956), pp. 1–28 and 354–57. A Japanese particle theorist's survey of developments in elementary-particle theory and field theory from the early 1920s to the mid-1950s. Contains references to many pioneering papers. (I)
118. **"Point-Counterpoint in Physics: Theoretical Prediction and Experimental Discovery of Elementary Particles,"** J. Leite Lopes, Fundam. Sci. **6**, 165–77 (1985). A physicist's sketch of the prediction and discovery of particles from the electron to the W and Z bosons. (I)
119. **"The Rules of Scientific Discovery Demonstrated from Examples of the Physics of Elementary Particles,"** Herbert Pietschmann, Found. Phys. **8**, 905–19 (1978). Discusses how Popper's rules of scientific progress were applied by working physicists in the discoveries of the positron, the neutrino, the Ω^- hyperon, and other particles. (I)
120. **"Who Named the =ON's?"** Charles T. Walker and Glen A. Slack, Am. J. Phys. **38**, 1380–89 (1970). On the history of the names of the electron, neutron, proton, fermion, and other, *-on*'s. (E)

B. Concept-oriented works

These selections have some thread of history and are directed toward the layman.

121. **From X-Rays to Quarks: Modern Physicists and Their Discoveries,** Emilio Segrè (Freeman, San Francisco, 1980). An entertaining "impressionistic view" of major events in physics since 1895. Chapters 9, 11, 12, and 13 deal with aspects of modern particle physics. (E)
122. **"The Voyage into Matter,"** Part II of *The Cosmic Code: Quantum Physics as the Language of Nature,* Heinz R. Pagels (Simon and Schuster, New York, 1982), pp. 191–322. (E)
123. **From Atoms to Quarks: An Introduction to the Strange World of Particle Physics,** James S. Trefil (Scribner's, New York, 1980). (E)
124. **The Story of Quantum Mechanics,** Victor Guillemin (Scribner's, New York, 1968), Chaps. 9–14, pp. 120–217. (E)
125. **Search for a Supertheory: From Atoms to Superstrings,** Barry Parker (Plenum, New York, 1987). A popular account of particle physics from 1920 to the 1980s, with emphasis on developments since 1970. (E)
126. **The Particle Hunters,** Yuval Ne'eman and Yoram Kirsh (Cambridge U. P., New York, 1986). A popular account of elementary-particle physics since the turn of the century. In spite of its title, the book is not biographically structured. (E)
127. **The Particle Explosion,** Frank Close, Michael Marten, and Christine Sutton (Oxford U. P., New York, 1987). A popular account of particle discoveries since the turn of the century. (E)
128. **The Quest for Quarks,** Brian McCusker (Cambridge U. P., New York, 1983). A short, popular account of elementary-particle physics. Half of the book deals with the idea of and search for quarks. (E)
129. **Elementary Particles: A Short History of Some Discoveries in Atomic Physics,** Chen Ning Yang (Princeton U. P., Princeton, NJ, 1961). Based on a series of public lectures delivered at Princeton in November 1959. Briefly covers particle discoveries since the turn of the century. (E)
130. **The Discovery of Subatomic Particles,** Steven Weinberg (Scientific American Library, New York, 1983). A historically sensitive particle theorist's nonmathematical account of the discoveries of the electron, proton, and neutron. (E)
131. **From Quarks to the Cosmos: Tools of Discovery,** Leon M. Lederman and David N. Schramm (Scientific American Library, New York, 1989). An up-to-date account—by an experimental particle physicist and a theoretical astrophysicist—of the development of 20th-century particle physics and cosmology. Focuses on the tools (e.g., accelerators, detectors, and telescopes) that have enabled that development and on the convergence of the two disciplines. (E)
132. **"The Early Universe"** and **"Wild Ideas,"** Parts II and III of *Perfect Symmetry: The Search for the Beginning of Time,* Heinz R. Pagels (Simon and Schuster, New York, 1985), pp. 157–349. Describes the development of ideas about the origin and evolution of the universe, and covers the recent interface of elementary-particle physics and cosmology. (E)

VI. HISTORIES OF SPECIFIC TIMES AND EVENTS: A CHRONOLOGY OF ELEMENTARY-PARTICLE PHYSICS

A. Prelude to a discipline: Elementary particles before 1930

The first elementary particle, in a reasonably modern sense, was the electron. From about 1895 to about 1910, physicists and chemists widely assumed electrons—negative corpuscles, as well as positive ones in some theories—to be the basic constituents of matter. Around 1910 the electron of J. J. Thomson and H. A. Lorentz was recognized to carry a negative, indivisible charge.

On the early development (before the late 1890s) of the concept of the fundamental unit of electricity, see:

133. **"Evolution of the Concept of the Elementary Charge,"** L. Marton and C. Marton, Advances in Electronics and Electron Phys. **50**, 449–72 (1980). A historically perceptive article on the development of the concept from Benjamin Franklin to J. J. Thomson. (I)
134. **"George Johnstone Stoney, F.R.S., and the Concept of the Electron,"** J. G. O'Hara, Notes Rec. R. Soc. Lond. **29**, 265–76 (1975). Stoney coined the name "electron" in 1891, having originally suggested (in 1874) the term "electrine" to denote an electrolytic unit of charge. (I)
135. **"Concept and Controversy: Jean Becquerel and the Positive Electron,"** Helge Kragh, Centaurus **32**, 203–40 (1989). Covers the prehistory of the electron and also the controversy surrounding Becquerel's 1907 claim to have discovered positive electrons. The outcome of this debate was that "the positive electron was declared dead and buried and virtually disappeared from physics until it reappeared in 1931-32 under very different circumstances." (A)

On the discovery of the electron, see:

136. **The Discovery of the Electron: The Development of the Atomic Concept of Electricity,** David L. Anderson (Van Nostrand, Princeton, NJ, 1964). Traces the series of experimental and conceptual developments that, during the period 1890–1920, resulted in the modern idea of the electron. (I)
137. **"Cathode Rays and the Discovery of the Electron,"** Chap. 2 of *Discoveries in Physics* (Supplemental Unit B, Project Physics Course), David L. Anderson (Holt, Rinehart, and Winston, New York, 1973), pp. 32–45. A summary of the discovery and identification of cathode rays. (E)
138. **"Corpuscles, Electrons and Cathode Rays: J. J. Thomson and the 'Discovery of the Electron,' "** Isobel Falconer, Br. J. Hist. Sci. **20**, 241–76 (1987). A detailed, critical examination of Thomson's so-called "discovery of the electron." (A)
139. **"Arthur Schuster, J. J. Thomson, and the Discovery of the Electron,"** Stuart M. Feffer, Hist. Stud. Phys. Biol. Sci. **20**, 33–61 (1989). Discusses the similarities and differences between the approaches of Schuster (head of the physical laboratory at Victoria College, Manchester) and Thomson (head of the Cavendish Laboratory at Cambridge) in their separate but contemporaneous investigations of the discharge of electricity through gases during the 1880s and 1890s. (A)
140. **"J. J. Thomson and the Discovery of the Electron,"** George P. Thomson, Phys. Today **9** (8), 14–23 (Aug. 1956). Reprinted in Ref. 65, pp. 289–93. An account by a leading physicist, also the son of J. J. Thomson, discoverer of the electron (or cathode-ray "corpuscle," as he preferred to call it). (E)
141. **"The Discovery of the Electron,"** G. E. Owen, Ann. Sci. **11**, 173–82 (1955). (I)

142. "**The Discovery of the Beta Particle,**" Marjorie Malley, Am. J. Phys. **39**, 1454–60 (1971). Reprinted in *Physics History from AAPT Journals*, edited by Melba Newell Phillips (American Association of Physics Teachers, College Park, MD, 1985), pp. 83–90. On the identification of β rays with electrons around the turn of the century. (I)

Robert A. Millikan, who measured the elementary charge in a series of experiments between 1906 and 1914, was criticized by Felix Ehrenhaft, who argued that there in fact existed subelectronic charges, but most scientists rejected Ehrenhaft's claim.

143. **"Editor's Introduction,"** Jesse W. M. DuMond, in Robert Andrews Millikan's *The Electron: Its Isolation and Measurement and the Determination of Some of Its Properties* (University of Chicago Press, Chicago, 1963), pp. xi–lvii. A sketch of Millikan's career, including a section on the "Development of Our Knowledge of the Electron from 1897 to 1947." (E)

144. **"Subelectrons, Presuppositions, and the Millikan-Ehrenhaft Dispute,"** Gerald Holton, Hist. Stud. Phys. Sci. **9**, 161–224 (1978). Reprinted in his *The Scientific Imagination: Case Studies* (Cambridge U. P., New York, 1978), pp. 25–83. A detailed account of the debate, and analysis of the measuring methods of the two protagonists. "This study centers on events, in the years around 1910, that led two physicists into exactly opposite directions—one to "success" (and the Nobel Prize), the other to "failure" (and eventually a broken spirit). Failures are not remembered in science, and they are rarely analyzed in histories of science. Hence today this controversy is virtually forgotten." (A)

145. **"Electrons or Subelectrons? Millikan, Ehrenhaft and the Role of Preconceptions,"** Gerald Holton, in Ref. 42, pp. 266–89. A summary of Ref. 144. (I)

146. **"Millikan's Published and Unpublished Data on Oil Drops,"** Allan Franklin, Hist. Stud. Phys. Sci. **11**, 185–201 (1981). A careful analysis of Millikan's method and selection of "good" data. (See also Ref. 113.) (A)

147. **"Did Millikan Observe Fractional Charges on Oil Drops?"** William M. Fairbank, Jr., and Allan Franklin, Am. J. Phys. **50**, 394–97 (1982). Reanalyzing Millikan's 1913 data, the authors "find strong evidence in favor of charge quantization and no convincing evidence for fractional residual charges on the oil drops." (See also Ref. 113.) (I)

148. **"Ehrenhaft, the Subelectron and the Quark,"** P. A. M. Dirac, in Ref. 42, pp. 290–93. Presents a personal recollection about Ehrenhaft and comments on one of Millikan's discarded measurements, which showed a "quark charge" of $\frac{1}{3}e$. (A)

149. **"Electron Physics in America,"** Karl K. Darrow, Phys. Today **9** (8), 23–27 (Aug. 1956). Recollections of Millikan, E. H. Hall, C. J. Davisson, and other American electron physicists before 1930. (E)

On the electron in atomic models and chemistry before quantum mechanics, see:

150. **Electrons and Valence: Development of the Theory, 1900–1925,** Anthony N. Stranges (Texas A&M U. P., College Station, 1982). A comprehensive account, focusing on the chemists' conception of the electron and its use in valence theories. (A)

151. **"Bohr's Atomic Theory and the Chemists, 1913–1925,"** Helge Kragh, Rivista di Storia della Scienza **2**, 463–86 (1985). Discusses the tension between physicists' and chemists' conceptions of the electron and its role in atomic theory. (A)

On classical (nonrelativistic and relativistic) theories of the electron, see:

152. **"The Early History of the Theory of the Electron: 1897–1947,"** A. Pais, in Ref. 56, pp. 79–93. (I)

153. **"The Electron: Development of the First Elementary Particle Theory,"** Fritz Rohrlich, in Ref. 43, pp. 331–67. Covers the period 1880–1970. (I)

154. **"A Short History of the Classical Theory of Charged Particles,"** Chap. 2 of *Classical Charged Particles: Foundations of Their Theory,* F. Rohrlich (Addison-Wesley, Reading, MA, 1965), pp. 8–25. Surveys the development, from 1880 to 1950, of the basic ideas underlying the modern theory of classical electrons. (A)

The hydrogen nucleus became recognized as an elementary particle around 1912 and was dubbed the "proton" in 1920. This particle's emergence damped the unitary view of material composition, which the electron theorists had earlier urged, and until the early thirties matter was believed to consist solely of electrons and protons. The accepted model of the atomic nucleus involved both these particles, sometimes with one or more protons orbiting around a more central nuclear region composed of protons and electrons, as was suggested by Ernest Rutherford around 1920.

155. **"The Nuclear Electron Hypothesis,"** Roger H. Stuewer, in Ref. 172, pp. 19–67. Looks at the development of the idea of the nuclear electron from 1911 to 1934, and demonstrates that the electron was not automatically "expelled from the nucleus" with Chadwick's discovery of the neutron. (I)

156. **"Rutherford's Satellite Model of the Nucleus,"** Roger H. Stuewer, Hist. Stud. Phys. Biol. Sci. **16**, 321–52 (1986). Includes discussion of other hypothetical nuclear particles (proton–electron composites) of c. 1920. (A)

The photon, introduced as the light quantum by Einstein in 1905, did not count as a proper elementary particle until the mid-20s. Its checkered history can be followed in:

157. **The Tiger and the Shark: Empirical Roots of Wave–Particle Dualism,** Bruce R. Wheaton (Cambridge U.P., New York, 1983). On the gradual acceptance of the photon picture and wave–particle dualism between 1896 and 1925. (A)

158. **"Symmetries of Matter and Light: Early Reactions to the Light-quantum,"** Bruce R. Wheaton, in Ref. 44, pp. 279–96. Considers briefly the competition between two models of light, 1900–25. (A)

159. **The Compton Effect: Turning Point in Physics,** Roger H. Stuewer (Science History, New York, 1975). Provides a detailed history of the photon until 1927. (A)

160. **"G. N. Lewis on Detailed Balancing, the Symmetry of Time, and the Nature of Light,"** Roger H. Stuewer, Hist. Stud. Phys. Sci. **6**, 469–511 (1975). Discusses Lewis's "photon" of 1926, a particle that differed significantly from Einstein's light quantum. (A)

161. **"The Development of Attitudes to the Wave–Particle Duality of Light and Quantum Theory, 1900–1920,"** John Hendry, Ann. Sci. **37**, 59–80 (1980). (A)

162. **"Evolution of the Modern Photon,"** Richard Kidd, James Ardini, and Anatol Anton, Am. J. Phys. **57**, 27–35 (1989). (I)

B. The birth of elementary-particle physics (1930–47)

Particle physics, in its modern sense, emerged in the early 30s with the breakdown of the two-particle paradigm, according to which the electron and the proton were the sole constituents of matter. This process was initiated by Pauli's and Dirac's ideas of the neutrino and the antielectron, respectively, and was completed with the experimental discovery of two new particles, the neutron and the positron, in 1932, a year that has become known as the "annus mirabilis" of nuclear and particle physics.

163. **"The Birth of Elementary Particle Physics: 1930–1950,"** Laurie M. Brown and Lillian Hoddeson, in Ref. 38, pp. 3–36. An excellent survey of major developments during the period. (E)

164. **"The Birth of Elementary-Particle Physics,"** Laurie M. Brown and Lillian Hoddeson, Phys. Today **35** (4), 2–9 (1982). Reprinted in Ref. 65, pp. 346–53. An abridged version of Ref. 163. (E)

165. **"The Wonder Year 1932: Neutron, Positron, Deuterium, and Other Discoveries,"** Chap. 9 of Ref. 121, pp. 175–99. (E)

166. **"1932—Moving into the New Physics,"** Charles Weiner, Phys. Today **25** (5), 40–49 (1972). Reprinted in Ref. 65, pp. 332–39. On the exciting events of the early 1930s and how they changed the pace and social structure of physics research. (E)

167. **Introduction to Part I** ("Three Famous Experiments of 1932"),

John Hendry, in Ref. 445, pp. 7–30. A brief history of Chadwick's discovery of the neutron, Blackett and Occhialini's demonstration of the existence of the positron, and Cockcroft and Walton's splitting of the atom. (I)

168. **"Some Recollections from the Early Days of Particle Physics,"** N. Kemmer, in *Hadronic Interactions of Electrons and Photons*, edited by J. Cumming and H. Osborn (Academic, New York, 1971), pp. 1–16. A physicist's recollections about particle physics in Europe in the late 1930s and about the reception of Yukawa's meson theory. (A)

169. **"Particle Physics since 1930: A History of Evolving Notions of Nature's Simplicity and Uniformity,"** Visvapriya Mukherji and Sudhansu Kumar Roy, Am. J. Phys. **50**, 1100–1103 (1982). (E)

The ground shared by elementary-particle physics and nuclear physics during the early years is treated in the following histories that focus on aspects of nuclear physics.

170. **Exploring the History of Nuclear Physics,** edited by Charles Weiner (American Institute of Physics, New York, 1972). Proceedings of the 1967 and 1969 AIP Conferences on the History of Nuclear Physics. (I, A)

171. **Nuclear Physics in Retrospect: Proceedings of a Symposium on the 1930s,** edited by Roger H. Stuewer (University of Minnesota Press, Minneapolis, 1979). Proceedings of the Symposium on the History of Nuclear Physics held at the University of Minnesota in May 1977. (I, A)

172. **Otto Hahn and the Rise of Nuclear Physics,** edited by William R. Shea (Reidel, Boston, 1983). Contains 10 articles, mainly on the development on nuclear physics, 1910–40. (I, A)

173. **"From the Discovery of the Neutron to the Discovery of Nuclear Fission,"** Edoardo Amaldi, Phys. Reports **111**, 1–331 (1984). A leading physicist's panoramic survey of nuclear physics during the 1930s. Includes references to over 900 articles and books, most of them primary sources. (A)

174. **Part I** of Ref. 77, pp. 1–118. Includes a historically informed survey of nuclear theory and its interface with particle theory from 1932 to 1940. (A)

175. **"Werner Heisenberg and the Beginning of Nuclear Physics,"** Arthur I. Miller, Phys. Today **38** (11), 60–68 (1985). (E)

176. **"Zur Geschichte des Begriffes 'Isospin,' "** G. Rasche, Arch. Hist. Exact Sci. **7**, 257–76 (1971). On Heisenberg's introduction of isospin in 1932 and the development of the concept in nuclear and particle theory during the remainder of the decade. (A)

177. **"Remarks on the History of Isospin,"** Laurie M. Brown, in Ref. 63, pp. 39–47. "The history of the isospin concept is reviewed from the introduction of the formalism by Heisenberg in 1932 to the isospin selection rules of Adair, Radicati, and Gell-Mann and Telegdi of the early 1950s, and the significance of the concept is assessed." (I)

178. **"Historical Introduction to Isospin,"** D. H. Wilkinson, in *Isospin in Nuclear Physics*, edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969), pp. 3–13. A survey of the development of theories of isospin from Heisenberg (1932) to the mid-1960s. (A)

179. **"Isospin,"** N. Kemmer, in Ref. 40, pp. 359–90. A description of the history of isospin from 1932 to 1954, with emphasis on the introduction of the concept into field theories in the late 1930s. (A)

Cloud chamber observations of cosmic radiation were the main source of knowledge in particle physics until the 50s. From the late 20s, cosmic-ray research was dominated by American physicists, including Millikan's group at Caltech and Arthur H. Compton's at Chicago. In the early 30s, much effort went into determining the basic nature of the radiation; Millikan argued that the bulk of the primary cosmic radiation was composed of energetic photons, while Compton believed that it consisted mainly of protons. Aspects of cosmic-ray research through the early 50s are addressed in Refs. 45 and 82 and in:

180. **Cosmic Rays,** Bruno Rossi (McGraw-Hill, New York, 1964). A semipopular history by a leading researcher. (I)

181. **Cosmic Rays,** Michael W. Friedlander (Harvard U. P., Cambridge, MA, 1989). An up-to-date, comprehensive, popular history of the subject, with especially good treatment of its relationship to elementary-particle physics and geophysics. (E)

182. **"The History of Cosmic Rays,"** W. F. G. Swann, Am. J. Phys. **29**, 811–16 (1961). (E)

183. **"The Early History of Cosmic Ray Research,"** Qiaozhen Xu and Laurie M. Brown, Am. J. Phys. **55**, 23–33 (1987). Reviews developments from 1900 to the late 1920s. (I)

184. **"Technology and the Process of Scientific Discovery: The Case of Cosmic Rays,"** Charles A. Ziegler, Tech. & Cult. **30**, 939–63 (1989). Discusses the interactive relationship that existed from 1909 to 1932 between balloon technology and advances in measuring instruments for cosmic rays. (I)

185. **"History of the Discovery of Elementary Particles in Cosmics [*sic*] Rays,"** I. V. Dorman, in *History of Mathematical and Physical Sciences in the U.S.S.R.* (Acta Historiae Rerum Naturalium necnon Technicarum, Special Issue 18), edited by Luboš Nový (Institute of Czechoslovak and General History CSAS, Prague, 1982), pp. 369–406. A nice summary of studies of the cosmic radiation from the early 1900s through the discoveries of the positron, muon, and pion. (E)

186. **"The Role of Cosmic Rays in the Development of Particle Physics,"** Ch. Peyrou, in Ref. 40, pp. 7–68. An excellent survey of the period 1930–55. (I)

187. **"Early Days in Cosmic Rays,"** Bruno Rossi, Phys. Today **34** (10), 34–41 (1981). Reprinted in *Astrophysics Today*, edited by A. G. W. Cameron (American Institute of Physics, New York, 1984), pp. 18–25. Personal recollections of the period 1929–32, when Rossi worked in Arcetri, Italy. (A longer version of this essay appears in Ref. 45. See also Ref. 490, Chap. 1.) (E)

188. **"Birth Cries of the Elements: Theory and Experiment along Millikan's Route to Cosmic Rays,"** Robert H. Kargon, in *The Analytic Spirit: Essays in the History of Science in Honor of Henry Guerlac*, edited by Harry Woolf (Cornell University Press, Ithaca, NY, 1981), pp. 309–29. Covers the background for Millikan's view of cosmic radiation, including his political and religious beliefs. (I)

189. **"The Evolution of Matter: Nuclear Physics, Cosmic Rays, and Robert Millikan's Research Program,"** Robert H. Kargon, in Ref. 172, pp. 69–89. Treats the same subject as Ref. 188. (I)

190. **"Cosmic Ray Romancing: The Discovery of the Latitude Effect and the Compton–Millikan Controversy,"** M. de Maria and A. Russo, Hist. Stud. Phys. Biol. Sci. **19**, 211–67 (1989). A detailed account of the debate (1930–36) about the "latitude effect"—the latitude-dependent geographical distribution of cosmic-ray particles, which served to indicate their nature. Discusses the views of the two contestants, emphasizing their scientific, personal, and ideological differences. (A)

191. **"Unraveling the Particle Content of Cosmic Radiation,"** Carl D. Anderson with Herbert L. Anderson, in Ref. 38, pp. 131–54. Based in part on Ref. 215. A personal account of C. D. Anderson's involvement in cosmic-ray research from 1930 to 1947. (Another version of this essay appears in Ref. 45.) (I)

The neutron, a particle that Rutherford had anticipated since 1920, was detected by James Chadwick in 1932, and gradually physicists recognized it to be a true elementary particle and not a proton–electron composite. The neutron's history until the late 30s is treated in Refs. 79, 155, and 445 and in:

192. **"A History of Neutrons and Nuclei,"** Norman Feather, Contemp. Phys. **1**, 191–203 and 257–66 (1960). Traces the history of the concepts of "nucleus" and "neutron" from 1898 to the late 1930s. (I)

193. **"On the History of the Neutron,"** Bernd Kröger, Physis **22**, 175–90 (1980). A survey of the main developments in the neutron concept between 1898 and 1933. (I)

194. **"Pourquoi ni Bothe ni les Joliot-Curie n'ont découvert le neutron?"** Jules Six, Revue d'Histoire des Sciences **41**, 1–24 (1988). An analysis of the reasons why German and French physicists failed to discover the neutron in advance of Chadwick. (A)

195. **The Discovery of the Neutron and Its Effects upon Physics,** Symposium III in *Proceedings of the Tenth International Congress of the History of Science* (1962) (Hermann, Paris, 1964), Vol. 1, pp. 119–

62. Contains the papers "Nuclear Physics Without the Neutron: Clues and Contradictions," E. M. Purcell; "The Experimental Discovery of the Neutron," N. Feather (reprinted in Ref. 445); "The Consequences of the Discovery of the Neutron," E. Segrè; and "Some Personal Notes on the Search for the Neutron," J. Chadwick (reprinted in Ref. 445 and updated in Ref. 196). (I)

196. "Discovery of the Neutron," Chap. 9 of Ref. 68, β 1972, pp. 191–215. Includes an "updated" version of Chadwick's "Some Personal Notes..." (see Ref. 195) and reprints his famous (1932) paper from *Proceedings of the Royal Society.* (E)

197. La découverte du neutron (1920–1936), Jules Six (Centre National de la Recherche Scientifique, Paris, 1987). Includes a chronology of particle physics, 1895–1936, and a detailed analysis of the discovery of the neutron. (A)

198. "The Impact of the Neutron: Bohr and Heisenberg," Joan Bromberg, Hist. Stud. Phys. Sci. **3**, 307–41 (1971). Examines the reactions of Bohr and Heisenberg to the announcement of the discovery of the neutron, and the event's impact on their ideas about the atomic nucleus. Covers the years 1929–32. (A)

199. "The Neutron: The Impact of Its Discovery and Its Uses," Eugene P. Wigner, in Ref. 171, pp. 159–73. A physicist's sketch of the neutron's history, 1920–64. (A)

200. "Personal Notes on Neutron Work in Rome in the 30s and Post-war European Collaboration in High-Energy Physics," Edoardo Amaldi, in Ref. 42, pp. 294–351. (A)

Another important particle—although not elementary in nature—to be discovered in the early 30s was the deuteron.

201. "The Naming of the Deuteron," Roger H. Stuewer, Am. J. Phys. **54**, 206–18 (1986). Recounts the discussions, from 1933 to 1935, between E. O. Lawrence, G. N. Lewis, E. Rutherford, H. Urey, and others, concerning the name and nature of the deuteron. (I)

202. "Harold Urey and the Discovery of Deuterium," Ferdinand G. Brickwedde, Phys. Today **35** (9), 34–39 (1982). (E)

In 1930 Pauli proposed the concept of the neutrino, which would conveniently conserve energy, momentum, and spin in β decay; this fourth elementary particle was at first thought to be a constituent of the nucleus and called the "neutron." But the hypothetical neutrino did not become respectable until the advent of Fermi's theory of β decay in 1933–34, and the particle was not actually detected until the 50s (see Refs. 297–301).

203. "The Idea of the Neutrino," Laurie M. Brown, Phys. Today **31** (9), 23–28 (1978). Reprinted in Ref. 65, pp. 340–45. Details Pauli's proposal and the reactions to it. (E)

204. Wolfgang Pauli: Wissenschaftlicher Briefwechsel mit Bohr, Einstein, Heisenberg u. a., edited by Karl von Meyenn (Springer-Verlag, New York, 1985); Vol. 2, Pauli's invention and development of the neutrino concept can be traced through his correspondence from 1930 to 1939. (A)

205. "Pauli, das Neutrino und die Entdeckung des Neutrons vor 50 Jahren," Karl von Meyenn, Naturwissenschaften **69**, 564–73 (1982). On the genesis and early development of Pauli's theory, 1929–33. "The factual information now available from the Pauli Correspondence [Ref. 204] shows the neutrino so to speak, as a by-product of a much more comprehensive revision of the foundations of physics, to which end the efforts of several great theoreticians were directed in order to overcome the theoretical difficulties confronting nuclear physics at the beginning of the 1930s." (A)

206. "Nuclear Structure and Beta Decay (1932–1933)," Laurie M. Brown and Helmut Rechenberg, Am. J. Phys. **56**, 982–88 (1988). On the history of Fermi's theory of β decay, its importance for the neutron–proton picture of the nucleus, and the 1933 Solvay Conference. (I)

207. "Experiment and the Development of the Theory of Weak Interactions: Fermi's Theory," Allan Franklin, in *PSA 1986,* Vol. 2, edited by Arthur Fine and Peter Machamer (Philosophy of Science Association, East Lansing, MI, 1987), pp. 163–79. "The fallibility and corrigibility of experimental results, and of the confirmation or refutation based on those results, is illustrated in the 1930s history of Fermi's theory of [β] decay. Early results favored the competing theory of Konopinski and Uhlenbeck. It was found that there were experimental difficulties along with an incorrect theoretical comparison. When the experiments were corrected and the proper theoretical calculations made, the evidence favored Fermi and refuted Konopinski and Uhlenbeck." (See also Ref. 114.) (I)

208. "Fermi's Theory of Beta Decay," Fred L. Wilson, Am. J. Phys. **36**, 1150–60 (1968). A translation of Fermi's classic paper of 1934, with a brief historical introduction. (A)

See also Refs. 114, 306, and 307.

In 1930 Dirac announced his idea of "holes" in a "sea" of negative energy. At first he suggested that the holes were protons, but in 1931 he decided that they were new, positive particles of electronic mass, "antielectrons." On Dirac's theory of the electron and his associated theory of antiparticles, see:

209. "Antimatter: Its History and Its Properties," Michael Martin Nieto and Richard J. Hughes, in *Antiproton Science and Technology,* edited by B. W. Augenstein, B. E. Bonner, F. E. Mills, and M. M. Nieto (World Scientific, Singapore, 1988), pp. 228–48. Sketches the developments in quantum theory and relativity theory that led to the Dirac equation and its prediction of antimatter. Also summarizes the discoveries of the positron and the antiproton and discusses the modern understanding of antimatter in terms of the CPT theorem. (I)

210. "Evaluations of Dirac's Electron, 1928–1932," Donald Franklin Moyer, Am. J. Phys. **49**, 1055–62 (1981). Surveys the reactions of Bohr and other physicists to Dirac's speculations about negative-energy electrons. (I)

211. "The Dream of Philosophers," Chap. 5 of Ref. 480, pp. 87–117. On the development and reception of Dirac's hole theory from 1929 to 1933. (A)

212. "The Concept of Particle Creation Before and After Quantum Mechanics," Joan Bromberg, Hist. Stud. Phys. Sci. 7, 161–83 (1976). Focuses on the ideas of particle creation and annihilation in astrophysics in the early 1920s and contrasts these ideas with Dirac's later theory. (A)

In 1932, while performing cosmic-ray research that was unconnected with Dirac's theory, Carl D. Anderson announced his detection of the positron, which was soon identified with Dirac's antielectron. Working independently of Anderson, Patrick Blackett and Giuseppe Occhialini performed experiments that confirmed the positron's existence.

213. "The Positron," Chap. 9 of *The Concept of the Positron: A Philosophical Analysis,* Norwood Russell Hanson (Cambridge U. P., Cambridge, 1963), pp. 135–65. A philosophically oriented history of the concept and the discovery of the positron. Argues that the discovery process involved three *different* particles: the Dirac particle, the Anderson particle, and the Blackett–Occhialini particle. (I)

214. "The Discovery of the Positron," Michelangelo De Maria and Arturo Russo, Rivista di Storia della Scienza **2**, 237–86 (1985). A detailed historical account of the work of Anderson and of Blackett and Occhialini in 1932 and 1933. (A)

215. "Early Work on the Positron and Muon," Carl D. Anderson, Am. J. Phys. **29**, 825–30 (1961). Reprinted in *Physics History from AAPT Journals* (see Ref. 142), pp. 137–42. Anderson's recollections of his discoveries of the positron and the muon in 1932 and 1937. (See also Ref. 191.) (E)

216. "Vindications of Dirac's Electron, 1932–1934," Donald Franklin Moyer, Am. J. Phys. **49**, 1120–25 (1981). Surveys the effect of the detection of the positron on physicists' confidence in Dirac's relativistic quantum dynamics, and the problems that the particle posed for QED. (I)

Accounts of Blackett and Occhialini's work can also be found in Ref. 445.

The discovery of the positron inspired the Yugoslavian physicist Stjepan Mohorovicic in 1934 to conjecture the existence of electron–positron atoms. Not until 1951 was this kind of exotic atom, called "positronium," detected.

217. **"From 'Electrum' to Positronium,"** Helge Kragh, J. Chem. Educ. **67**, 196–97 (1990). Discusses Mohorovicic's speculations and the history of positronium until its discovery. (For details of the discovery itself, see Ref. 68, δ Volume, pp. 63–127.) (I)

Dirac's relativistic equation for the electron was applicable to any spin-1/2 particle, and thus his hole theory implied the existence of antiparticles in general, including an antiproton. Dirac hypothesized this particle in 1931, together with the magnetic monopole. While the monopole idea was ignored for many years, there was some interest in the negative proton in the 30s. See Ref. 294 and:

218. **"The Negative Proton: Its Earliest History,"** Helge Kragh, Am. J. Phys. **57**, 1034–39 (1989). On the place of the hypothetical "negative proton"—as distinguished from the antiproton—in the physics of the 1930s. (A)
219. **"Monopoles Before Dirac,"** John Hendry, Stud. Hist. Philos. Sci. **14**, 81–87 (1983). Considers the idea of magnetic monopoles in British physics of the 1920s. (A)
220. **"The Concept of the Monopole: A Historical and Analytical Case-Study,"** Helge Kragh, Stud. Hist. Philos. Sci. **12**, 141–72 (1981). Discusses the development of the idea of the monopole from 1931 to 1978, and compares the acceptance of monopoles and tachyons. (I)
221. **"Just a Disappointment,"** Chap. 10 of Ref. 480, pp. 205–22. An account of Dirac's involvement with monopoles from 1931 to his death in 1984. (A)
222. **"On the Dirac Magnetic Poles,"** Edoardo Amaldi and Nicola Cabibbo, in Ref. 56, pp. 183–212. A semihistorical survey of the theoretical development of Dirac's ideas on monopoles, and of experiments (mainly in the 1960s) to detect the hypothetical particles. (A)

After the establishment of the Dirac equation and its successful prediction of the positron, several attempts were made to construct relativistically invariant first-order wave equations for particles with arbitrary spin. The first of these was proposed by Ettore Majorana in 1932, and during the following ten years Louis de Broglie, Alexandre Proca, Nicholas Kemmer, Homi Bhabha, and others tried to construct equations that would describe hypothetical particles.

223. **"Comments on a Paper by Majorana Concerning Elementary Particles,"** D. M. Fradkin, Am. J. Phys. **34**, 314–18 (1966). On Majorana's 1932 theory of particles with arbitrary integral or half-integral spin. (A)
224. **"Historical Development of the Bhabha First-Order Relativistic Wave Equations for Arbitrary Spin,"** R. A. Krajcik and Michael M. Nieto, Am. J. Phys. **45**, 818–21 (1977). Deals mainly with the period 1934–50. (A)

In the early thirties, quantum mechanics introduced the symmetry operations of P (parity), C (charge conjugation), and T (time reversal) into the description of elementary particles, and these concepts became increasingly important in later particle physics.

225. **"From Magnet Reversal to Time Reversal,"** Manuel G. Doncel, in Ref. 44, pp. 409–28. Covers time reversal in quantum mechanics and the earlier classical versions of the concept. Considers Wigner's introduction of the time reversal operator (in 1931–32) and its slow acceptance by physicists until it was "rediscovered" in the 1950s. (A)
226. **"Charge Conjugation,"** Louis Michel, in Ref. 44, pp. 389–405. On the development of the idea of charge conjugation from Dirac (1928–31) to the mid-1950s. (A)

Quantum theory faced a crisis during the early 30s because of its apparent inability to explain high-energy phenomena in the cosmic radiation. Quantum field theory, as developed by Heisenberg, Pauli, Dirac, Oppenheimer, and others, tried in vain to make sense of the absorption data, and many leading theorists believed that the failure necessitated radical alterations in quantum theory.

227. **"Cosmic Ray Showers, High Energy Physics, and Quantum Field Theories: Programmatic Interactions in the 1930s,"** David C. Cassidy, Hist. Stud. Phys. Sci. **12**, 1–39 (1981). A study of theoretical responses to cosmic-ray showers and absorption data in the 1930s, focusing on characteristic attitudes, styles, and research programs. Includes an account of the Bethe–Heitler theory. (A)

See also especially Refs. 232–34. The discovery of the "mesotron," or "heavy electron," that is, the muon, by Seth Neddermeyer and Carl Anderson in 1937 did much to restore confidence in existing theory, although it did not remove all difficulties. The discovery of the muon and its subsequent history are treated in Refs. 191 and 215 and in:

228. **"The Discovery of the Muon and the Failed Revolution Against Quantum Electrodynamics,"** Peter Galison, Centaurus **26**, 262–316 (1983). A detailed analysis of the discovery process, its background in cosmic-ray research, and the interaction between theory and experiment during the period 1932–38. (See also Ref. 112, Chap. 3.) (I)
229. **"Early Study of Muons and Muon Decay,"** M. Conversi, in Ref. 47, pp. 154–67. An experimenter's account of cosmic-ray research between 1929 and 1947, focusing on experiments that uncovered the muon and explored its behavior. (A)
230. **"From the Discovery of the Mesotron to That of Its Leptonic Nature,"** Marcello Conversi, in Ref. 41, pp. 1–20. The "tangled tale of the muon," from 1937 to 1949, including the author's personal recollections of muon experiments in Italy in the 1940s, which led to recognition that the particle is not a hadron. (I)
231. **"The Intriguing History of the μ Meson,"** Gilberto Bernardini, in Ref. 38, pp. 155–72. A survey of the history of the muon from its discovery in 1937 to the 1970s, by a veteran of cosmic-ray research. (E)

Before the discovery of the muon, the Japanese theorist Hideki Yukawa had proposed a theory of the strong nuclear force that incorporated a massive boson as the exchange particle carrying the force. When Yukawa's theory became known in Europe and America in 1937–38, his meson (the pion) was erroneously identified with the particle recently discovered by Anderson and Neddermeyer (the muon). This led to puzzles in the explanation of the cosmic radiation, but Yukawa's theory also stimulated the development of new theories of nuclear forces.

232. **"The Quantum Electrodynamical Analogy in Early Nuclear Theory, or the Roots of Yukawa's Theory,"** Olivier Darrigol, Revue d'Histoire des Sciences **41**, 225–97 (1988). On the crisis in quantum mechanics in the 1930s and the analogy between Yukawa's meson theory and QED. Focuses on the theories of Fermi, Yukawa, and Stückelberg during the period 1933–37. (A)
233. **"Anomalies and Statistical Explanation in Meson Theory,"** Chap. 6 of *Anomalies and Scientific Theories*, Willard C. Humphreys (Freeman, Cooper, San Francisco, 1968), pp. 247–97. "Starting with the problems about beta-decay, nuclear binding, and cosmic rays Yukawa framed an explanatory hypothesis designed to dispel all perplexity. When further anomalies threatened this hypothesis, deeper investigations were launched. *The H–D [hypothetico-deductive] model of theories notwithstanding, this is the normal course of scientific progress.*" (I)
234. **"Yukawa's Prediction of the Meson,"** Laurie M. Brown, Centaurus **25**, 71–132 (1981). A detailed study of the conceptual development of Yukawa's theory and its background in problems of nuclear and cosmic-ray physics. Also discusses the relation of the theory to Japanese culture. (A)
235. **"Hideki Yukawa and the Meson Theory,"** Laurie M. Brown, Phys.

Today **39** (12), 55–62 (1986). (E)

236. **"Yukawa and the Birth of Meson Theory,"** Joseph L. Spradley, Phys. Teach. **23**, 283–89 (1985). (See also Ref. 243.) (E)

237. **"Yukawa in the 1930s: A Gentle Revolutionary,"** Laurie M. Brown, in Ref. 66, pp. 1–21. A biography of Yukawa until the late 1930s, focusing on the origin and acceptance of his meson theory of nuclear forces. (A)

238. **"On the Establishment of the Yukawa Theory,"** Shoichi Sakata, Progr. Theor. Phys. Suppl. **41**, C8–C18 (1968). Recollections about Japanese particle physics in the 1930s, with emphasis on Yukawa. (A)

239. **"A Short History of the Meson Theory from 1935 to 1943,"** Viśvapriya Mukherji, Indian J. Hist. Sci. **6**, 75–101 and 117–34 (1971). (A)

240. **"A History of the Meson Theory of Nuclear Forces from 1935 to 1952,"** Viśvapriya Mukherji, Arch. Hist. Exact Sci. **13**, 27–102 (1974). (A)

241. **"The Impact of Yukawa's Meson Theory on Workers in Europe—A Reminiscence,"** N. Kemmer, Progr. Theor. Phys. Suppl. **Extra No.**, 602–8 (1965). (The journal's special issue is entitled "Commemoration Issue for the Thirtieth Anniversary of the Meson Theory by Dr. H. Yukawa.") (A)

242. **"Thirty Years of Mesons,"** J. Robert Oppenheimer, Phys. Today **19** (11), 51–58 (1966). (E)

Only around 1947 was it determined that the cosmic-ray particle of Neddermeyer and Anderson was a lepton and therefore not Yukawa's meson, but at about the same time, the correct Yukawa particle, the charged pion, was discovered by Cecil Powell and coworkers at the University of Bristol (see Refs. 285–87 and 446).

Japan, where meson theory had its origin, became a strong center for theoretical particle physics in the 30s and 40s, first through the important contributions of Yukawa, and slightly later through the work of Sin-itiro Tomonaga, Shoichi Sakata, and others. The technical, cultural, and social aspects of Japanese particle physics have recently been the subject of several detailed studies. In addition to selections in Refs. 50, 51, and 66, the following articles emphasize the national context of Japanese physics.

243. **"Particle Physics in Prewar Japan,"** Joseph L. Spradley, Am. Scientist **73**, 563–69 (1985). Based in part on Ref. 236. Reviews Japanese physics before Yukawa, including the contributions of H. Nagaoka, J. Ishiwara, and Y. Nishina. Surveys Yukawa's scientific training and career and the history of his meson theory, and comments on the "unique aspects of Japanese physics" that could account for "the [rapid] rate at which Western science was absorbed and original contributions were begun." (E)

244. **"Methodological Approaches in the Development of the Meson Theory of Yukawa in Japan,"** Mituo Taketani, in *Science and Society in Modern Japan: Selected Historical Sources,* edited by Shigeru Nakayama, David L. Swain, and Eri Yagi (MIT Press, Cambridge, MA, 1974), pp. 24–38. Discusses theoretical physics in Japan before Yukawa, and the political and philosophical circumstances that formed the background of Yukawa's proposal. (I)

245. **"Accounting for Science: The Impact of Social and Political Factors on Japanese Elementary Particle Physics,"** Morris Fraser Low, in Ref. 66, pp. 43–66. Examines the role that Taoism, Marxism, and other external factors played in Japanese theoretical physics of the 1930s and 1940s. (A)

Quantum electrodynamics (QED), pioneered by Dirac, Jordan, Pauli, and Heisenberg between 1926 and 1930, eventually became the dominant framework for theories in particle physics. However, at first QED was plagued by divergences and other difficulties, and its problems were not solved until after World War II. The following works address aspects of the early development of quantum field theory.

246. **"La genèse du concept de champ quantique,"** Olivier Darrigol, Annales de Physique **9**, 433–501 (1984). An account of the development of quantum field theory until 1932, focusing on the theories of Jordan and Dirac (1925–27). (A)

247. **"Cultural Traditions and Environmental Factors in the Development of Quantum Electrodynamics (1925–1933),"** Marcello Cini, Fundam. Sci. **3**, 229–53 (1982). Discusses the cultural and epistemological differences between German and British physicists, as reflected in early discussions about QED. Focuses on the differences between Jordan's and Dirac's versions of QED. (I)

248. **"Dirac's Quantum Electrodynamics and the Wave–Particle Equivalence,"** Joan Bromberg, in Ref. 42, pp. 147–57. On the structure of Dirac's theory of 1927. (I)

249. **"P. A. M. Dirac and the Formation of the Basic Ideas of Quantum Field Theory,"** B. V. Medvedev and D. V. Shirkov, Sov. Phys. Usp. **30**, 791–815 (1987). Commemorates the 60th anniversary of the publication of Dirac's seminal paper "The Quantum Theory of the Emission and Absorption of Radiation." Covers the origin and evolution of the basic concepts and representations of QFT "more from a logical than a historical aspect." Includes an annotated bibliography of important original sources. (A)

250. **"Quantum Theory of Fields (until 1947),"** Gregor Wentzel, in Ref. 61, pp. 48–77. Reprinted in Ref. 43, pp. 380–403. (A)

251. **"The Development of Field Theory in the Last 50 Years,"** Victor F. Weisskopf, Phys. Today **34** (11), 69–85 (1981). (E)

252. **"Quantum Electrodynamics: An Individual View,"** Julian Schwinger, in Ref. 40, pp. 409–24. Covers the development of QED from 1934 to the early 1950s, based on the way the author saw and participated in it. (I)

253. **"Some Chapters for a History of Quantum Field Theory 1938–1952,"** Silvan S. Schweber, in *Relativity, Groups and Topology II,* edited by B. S. DeWitt and R. Stora (North-Holland, New York, 1984), pp. 37–220. A comprehensive review covering both technical and institutional aspects of the field's history and also treating the renormalization theories of 1947–52. (A)

254. **"The Search for Unity: Notes for a History of Quantum Field Theory,"** Steven Weinberg, Dædalus **106** (4), 17–35 (Fall 1977). An excellent historical sketch, dealing mainly with developments through the late 1940s. (E)

255. **"The Ultimate Structure of Matter,"** Steven Weinberg, in Ref. 55, pp. 114–27. Based on a talk given in October 1981 at a celebration of the 50th anniversary of the founding of the Lawrence Berkeley Laboratory. Reviews the historical vacillation between particle and field interpretations of fundamental entities in 20th-century physics, beginning with the quantum field theory of Heisenberg and Pauli (1929) and the subsequent, opposing *S*-matrix approach of Wheeler and Heisenberg. (E)

256. **"The Empiricist Temper Regnant: Theoretical Physics in the United States 1920–1950,"** Silvan S. Schweber, Hist. Stud. Phys. Biol. Sci. **17**, 55–98 (1986). Contains a discussion of the Oppenheimer school of QED and the "American style" of physics exemplified by the new generation of quantum field theorists, among whom were J. Schwinger and R. P. Feynman. (A)

257. **"Further Developments in Visualizability,"** in *Imagery in Scientific Thought: Creating 20th-Century Physics,* Arthur I. Miller (Birkhäuser, Boston, 1984), pp. 154–73 and 179–83 (notes). Looks at theoretical particle physics from 1932 to 1949 within the context of changes in the concept of "visualizability." (I)

During the war, Heisenberg developed his *S*-matrix theory as an alternative to standard quantum field theory.

258. **"Some Remarks on the Early S-Matrix,"** Inge Grythe, Centaurus **26**, 198–203 (1982/83). A brief account of the development of the *S*-matrix theory from its birth in 1943 until it reached what seemed to be a dead end in 1947. Focuses on the contributions of C. Møller and S. T. Ma. (I)

259. **"The Early *S*-Matrix Theory and Its Propagation (1942–1952),"** Helmut Rechenberg, in Ref. 39, pp. 551–78. (I)

References 333–38 discuss later variants of the *S*-matrix approach and give comprehensive accounts of its development.

C. Elementary-particle physics comes of age (1947–61)

After World War II—the "physicists' war"—the entire enterprise of physics burgeoned. Elementary-particle physics developed into a well-defined discipline, whose maturity and distinctness were still evidently forthcoming in 1949 when George Gamow and C. L. Critchfield wrote (in their monograph *Theory of Atomic Nucleus and Nuclear Energy-Sources*):

> In fact, it is possible to develop the theory of the fundamental nuclear properties and the various nuclear reactions essentially on the basis of... interaction-laws between the nucleons from which the composite nuclei are built. Here lies a convenient, even though not very sharply defined, boundary between *nuclear physics proper*, and the next, as yet rather unexplored, division of the science of matter which can be called tentatively *the physics of elementary particles.*

In the early 50s an increasing reliance on complicated, powerful, expensive instrumentation precipitated the transformation of the subfield into the "Big Science" of high-energy physics, which became characterized by heavy governmental funding and collaborations often involving dozens of researchers. Most of this expansion took place in the United States. In 1950, when the number of detected or predicted elementary particles and antiparticles stood at around 20, the cosmic radiation was still the principal source of particles, but a few years later the new generation of accelerators and detectors significantly changed the experimental situation. The social, political, and institutional development of postwar physics is treated in Ref. 48 and in:

260. **The Physicists: The History of a Scientific Community in Modern America,** Daniel J. Kevles (Knopf, New York, 1978), Chaps. 21–24, pp. 324–409. Covers postwar research policy and the institutionalization of Big Science. (E)
261. **"Behind Quantum Electronics: National Security as Basis for Physical Research in the United States, 1940–1960,"** Paul Forman, Hist. Stud. Phys. Biol. Sci. **18**, 149–228 (1987). Looks at the confluence of the military, industry, and science in postwar America. Argues that the military patrons not only changed the priorities and social structure of American physics but also shaped its content and criteria of truth. (A)
262. **"Physics Between War and Peace,"** Peter Galison, in *Science, Technology, and the Military* (Sociology of the Sciences **12**, Yearbook 1988), edited by Everett Mendelsohn, Merritt Roe Smith, and Peter Weingart (Kluwer Academic, Boston, 1988), pp. 47–86. On the changes in physicists' mode of work during World War II. "The new breed of high-energy physicists were no longer taught to be both theorists and experimentalists—they chose one path or the other. In the place of physicist-craftsmen arose a collaborative association among theoretical and experimental physicists and engineers of accelerator, structural, and electrical systems." (I)
263. **"New Forms of Organization in Physical Research after 1945,"** L. Kowarski, in Ref. 42, pp. 370–401. (I)
264. **"Pragmatism in Particle Physics: Scientific and Military Interests in the Post-War United States,"** Andrew Pickering, in Ref. 49, pp. 174–83. Argues that U.S. elementary-particle theory in the 1950s became "characterized by a distinctive pragmatism," defined by "a split from fundamental theory, coupled with phenomenological utility," and explainable "in terms of the interweaving of scientific, political and military interests within post-war American society." (I)
265. **"The Khrushchev Détente and Emerging Internationalism in Particle Physics,"** Robert E. Marshak, Phys. Today **43** (1), 34–42 (1990). Traces the "flowering and wilting" of Soviet–American cooperation in particle physics during the Khrushchev détente of 1956–60, and details the role of the Rochester conferences in promoting international cooperation. (E)
266. **"Physics in the U.S.S.R.,"** E. P. Rosenbaum, Sci. Am. **195** (2), 29–35 (1956). Provides a survey of Soviet high-energy physics in the mid-1950s, based on interviews with R. E. Marshak and R. R. Wilson, who participated in the first postwar international physics conference to be held in the USSR (in May 1956). (E)

And the following works briefly survey the advances in postwar elementary-particle physics.

267. **"Beyond the Nucleus,"** Chap. 12 of Ref. 121, pp. 241–69. (E)
268. **"Pions to Quarks: Particle Physics in the 1950s,"** Laurie M. Brown, Max Dresden, and Lillian Hoddeson, in Ref. 39, pp. 3–39. A valuable overview of the period 1947–63. (E)
269. **"Pions to Quarks: Particle Physics in the 1950s,"** Laurie M. Brown, Max Dresden, and Lillian Hoddeson, Phys. Today **41** (11), 56–64 (1988). An abridged version of Ref. 268. (E)
270. **"Some Reflections on the History of Particle Physics in the 1950s,"** Silvan S. Schweber, in Ref. 39, pp. 668–93. A personal account by a leading physicist and historian. (I)

On the theoretical front, the period's first and most spectacular success was the development of renormalization QED around 1948. This theory—formulated independently by R. P. Feynman, Julian Schwinger, and Sin-itiro Tomonaga and made coherent by Freeman Dyson, who proved the equivalence of the three approaches—resolved the difficulties of the infinities that had earlier beset QED; and experiments measuring the Lamb shift and the magnetic moments of the electron and muon supported the theory's precise predictions for these quantities.

271. **"Old and New Fashions in Field Theory,"** Freeman J. Dyson, Phys. Today **18** (6), 21–24 (1965). Recollections of the years 1946–49 and comments on the situation in later years. "I spent my youth in defending Feynman's *S*-matrix heresy against Pauli's field-theoretical orthodoxy, and I shall spend my declining years in defending the field-theory heresy against Geoffrey Chew's *S*-matrix orthodoxy." (E)
272. **"Formation of the Renormalization Theory in Quantum Electrodynamics,"** Seiya Aramaki, Historia Sci. **32**, 1–42 (1987) [see Errata, Historia Sci. **34**, 95 (1988)]. Mainly covers the history of QED up to 1949, including measurements of fine structure and the Lamb shift. (A)
273. **"Development of the Renormalization Theory in Quantum Electrodynamics (I),"** Seiya Aramaki, in Ref. 66, pp. 97–116; "Development...(II)," Historia Sci. **37**, 91–113 (1989). Details the development of the theory from 1949 up to its application in electroweak theories of the late 1960s. (A)
274. **"Elements of a Scientific Biography of Tomonaga Sin-itiro,"** Olivier Darrigol, Historia Sci. **35**, 1–29 (1988). On Tomonaga's education in physics, his "super-many-time" theory, and his breakthrough in renormalization QED. Deals mainly with the years 1938–47. (A)
275. **"On the Fundamental Concepts in the Theory of Elementary Particles. I: History of the Tomonaga Theory of Fields,"** Mituo Taketani, Seitaro Nakamura, and Yoichi Fujimoto, in Ref. 64, pp. 433–39. Recollections of the formation of Tomonaga's QED, 1941–49. (A)
276. **"Development of Quantum Electrodynamics: Personal Recollections,"** Sin-itiro Tomonaga, Phys. Today **19** (9), 25–32 (1966); Ref. 43, pp. 404–12; Ref. 52c, pp. 126–36. Nobel lecture, delivered in May 1966. (E)
277. **"The Development of the Space-Time View of Quantum Electrodynamics,"** Richard P. Feynman, Science **153**, 699–708 (1966); Phys. Today **19** (8), 31–44 (1966); Ref. 52c, pp. 155–78; Ref. 73, Vol. 2, pp. 433–56. Nobel lecture, delivered in Dec. 1965. (E)
278. **"Feynman and the Visualization of Space-Time Processes,"** Silvan S. Schweber, Rev. Mod. Phys. **58**, 449–508 (1986). An excellent, detailed reconstruction of the genesis of Feynman's formulation of QED, focusing principally on the years 1947–50 and including a biography of Feynman up to 1950. (A)

279. **"Molecular Beam Experiments, the Lamb Shift, and the Relation Between Experiments and Theory,"** S. S. Schweber, Am. J. Phys. **57**, 299–308 (1989). Focuses on the experiments carried out in 1946–47 by W. E. Lamb and R. C. Retherford and by I. I. Rabi, J. E. Nafe, and E. B. Nelson to measure, respectively, the fine structure of hydrogen and the hyperfine structure of hydrogen and deuterium; and the influence of those experiments on QED. (I)

280. **"More on the Relationship Between Technically Good and Conceptually Important Experiments: A Case Study,"** Margaret Morrison, Br. J. Philos. Sci. **37**, 101–22 (1986). Elucidates the distinction between "technically good" and "conceptually important" experiments [see "What Makes a 'Good' Experiment?" A. D. Franklin, Br. J. Philos. Sci. **32**, 367–74 (1981)] by examining measurements of hydrogen's fine structure between 1934 and 1947 and their relation to QED. "The interesting point to note with respect to this discovery [the Lamb–Retherford experiment] is that similar anomalies [with the Dirac theory's representation of hydrogen's fine structure] were reported as early as 1934 yet little or no attention was paid to them until the 1947 discovery of Lamb and Retherford. It seems odd that this should be the case given that deviations from the Dirac theory were noted on *at least six* separate occasions during the period from 1934 to 1938, in contrast to only one confirming instance noted in the literature.... Their conceptual importance emerged solely as a result of the technical quality of the Lamb–Retherford experiment. Hence, it was primarily *because the experiment was technically good that it became conceptually important*, and as a result paved the way for quantum electrodynamics." (A)

281. **"Fine Structure in the Spectrum of Hydrogen,"** Chap. 7 of Ref. 69, pp. 99–119. On the Lamb–Retherford experiment of 1947. (I)

282. **"The Magnetic Moment of the Electron,"** Chap. 8 of Ref. 69, pp. 121–34. On the experiments of P. Kusch and H. M. Foley in 1947. (I)

283. **"The Electron Dipole Moment—A Case History,"** Polykarp Kusch, Phys. Today **19** (2), 23–35 (1966). Discusses the development of the molecular beam method and its application in the author's research on the hyperfine structure of atoms and in his discovery (with H. M. Foley) of the anomalous magnetic moment of the electron. (E)

284. **"Quantum Field Theory in Postwar Japan,"** Susumu Kamefuchi, in *Quantum Field Theory*, edited by Ferdinando Mancini (North-Holland, New York, 1986), pp. 1–17. A review of quantum field theory in Japan since 1945, with emphasis on the contributions of H. Umezawa. (I)

See also especially Refs. 251–54 and 472.

The decade 1947–56 saw an unanticipated proliferation of elementary particles, detected at first in cosmic-ray experiments and later by using high-energy accelerators. In 1946–47, charged pions and the first "V particles" were discovered. Then came the neutral pion, kaons, the antiproton, the antineutron, and others. Early attempts to explain the properties and behavior of some of the particles led to phenomenological theories such as "associated production" and the "strangeness" scheme. See Ref. 446 and:

285. **"The π Discovery,"** P. H. Fowler, in Ref. 41, pp. 35–50. An experimenter's account of the years 1946–50, emphasizing the emulsion and microscope techniques employed in the discoveries of the charged and neutral pions. (A)

286. **"The Birth of Pion Physics,"** D. H. Perkins, in Ref. 48, pp. 585–603. Emphasizes the experimental techniques involved in discovering the $\pi^{\pm}$ and π^0 and in determining the particles' properties. (A)

287. **"Origin of the Two-Meson Theory,"** R. E. Marshak, in *Shelter Island II*, edited by Roman Jackiw, Nicola N. Khuri, Steven Weinberg, and Edward Witten (MIT Press, Cambridge, MA, 1985), pp. 355–62. A personal account of the years 1947–48, when the μ and π mesons were established as separate particles. (I)

288. **"The Discovery of the V-Particles,"** G. D. Rochester, in Ref. 41, pp. 121–31. A brief, personal account of cosmic-ray research and the first V particles, by one of the discoverers. Covers the years 1937–49. (I)

289. **"The Discovery of the V-Particles,"** G. D. Rochester, in Ref. 47, pp. 173–94. A longer version of Ref. 288, with added, brief coverage of cloud chamber investigations of 1950–53. (A)

290. **"Cosmic-Ray Cloud-Chamber Contributions to the Discovery of the Strange Particles in the Decade 1947–1957,"** George D. Rochester, in Ref. 39, pp. 57–88. A personal account of the discovery of V particles, and the techniques used in other experiments by the Manchester group. (I)

291. **"The Early History of the Strange Particles,"** George D. Rochester, in Ref. 45, pp. 299–321. Discusses penetrating showers, V particles, K mesons, and hyperons, as they entered into research at Manchester from 1940 to 1956. (I)

292. **"The Early Times of Strange Particles Physics,"** Ch. Peyrou, in Ref. 48, pp. 604–51. "This talk tells the story of the strange particles discovery and the first studies of their properties. The first part describes the separation of the first hyperon, the Λ^0, from the K^0 meson and the discovery of the charged hyperons Σ and Ξ. The second part is devoted to the discovery of the many charged K's to be finally united as the many decay modes of a single K particle. The third part will tell how the most spectacular consequences of the "Gell-Mann, Nishijima" and "Gell-Mann, Païs" theories were verified: Associated production, Σ^0, Ξ^0, K_2^0 regeneration of K_1^0." (A)

293. **"Strangeness,"** M. Gell-Mann, in Ref. 40, pp. 395–402. A brief, personal account of how the author was led to introduce the concept of "strangeness" in 1952. (I)

294. **"The Detection of the Antiproton,"** J. L. Heilbron, in Ref. 48, pp. 161–217. Focuses on the history of the Berkeley Bevatron and the experiment in which the antiproton was detected by E. Segrè, O. Chamberlain, C. Wiegand, and T. Ypsilantis in 1955. "This discussion is preceded by an account of the antiproton before machines existed to make it and followed by a consideration of the lawsuit brought against Segrè and Chamberlain by Oreste Piccioni alleging theft of technical ideas fundamental to the success of the search for antiprotons." (I)

295. **"The Discovery of the Antiproton,"** Owen Chamberlain, in Ref. 39, pp. 273–84. (I)

296. **"Antinucleons,"** Emilio Segrè, Am. J. Phys. **25**, 363–69 (1957). (E)

Twenty-six years after its invention in 1930, Pauli's neutrino was finally confirmed in an experiment led by Clyde L. Cowan, Jr., and Frederick Reines.

297. **"Reality of the Neutrino,"** Chap. 12 of Ref. 69, pp. 191–209. On the experiment of Reines, Cowan *et al.* in 1956. (I)

298. **"The Neutrino,"** Chap. 4 of *Discoveries in Physics* (see Ref. 137), pp. 62–82. A summary of the invention of the neutrino and the discoveries of the e- and μ-neutrinos. Includes an annotated bibliography that lists many introductory-level resources. (E)

299. **"Anatomy of An Experiment: An Account of the Discovery of the Neutrino,"** Clyde L. Cowan, Ann. Rep. Smithsonian Inst. **1964**, 409–30. An entertaining, elementary treatment of the e-neutrino's history and discovery, including 12 photographs of the experimental apparatus. (E)

300. **"Detection of the Neutrino,"** Frederick Reines, in Ref. 39, pp. 359–66. (I)

301. **"The Early Days of Experimental Neutrino Physics,"** Frederick Reines, Science **203**, 11–16 (1979). Deals with the period 1950–56. (E)

In 1962 a second neutrino, the μ-neutrino, was found in an elaborate experiment led by Leon M. Lederman, Melvin Schwartz, and Jack Steinberger at Brookhaven National Laboratory.

302. **"Discovery of Two Kinds of Neutrinos,"** Chap. 5 of Ref. 68, α 1972, pp. 81–100. Reprints the discovery paper, and includes Schwartz's personal account of the research. (E)

303. **"The Two-Neutrino Experiment,"** Leon M. Lederman, Sci. Am. **208** (3), 60–70 (March 1963). (E)

304. **"The First High-Energy Neutrino Experiment,"** Mel Schwartz, Science **243**, 1445–49 (1989); Rev. Mod. Phys. **61**, 527–32 (1989). Nobel lecture, delivered in Dec. 1988. (I)

305. **"Observations in Particle Physics from Two Neutrinos to the Stan-**

dard Model," Leon M. Lederman, Science **244**, 664–72 (1989); Rev. Mod. Phys. **61**, 547–60 (1989). Nobel lecture, delivered in Dec. 1988. (I)

See also the short survey

306. **The Elusive Neutrino,** Jeremy Bernstein (U.S. Atomic Energy Commission, Washington, DC, 1969). A booklet that summarizes the history and physics of the neutrino for the layman. (E)

The most important experimental event during the period was the discovery of parity violation in weak interactions in 1957, which resolved the "τ-θ puzzle," that is, the question of why there seemed to exist *two* mesons with nearly identical masses and lifetimes but opposite parity. Motivating the experiments was T. D. Lee and C. N. Yang's discovery that the P symmetry (and the C symmetry, as well) had for years merely been *assumed* to be conserved in the weak interactions. The experimental demonstration of parity nonconservation has been examined as a prime example of the overthrow of a paradigmatic concept in modern physics.

307. **"The Neutrino,"** C. S. Wu, in Ref. 61, pp. 249–300. An experimenter's review of the neutrino hypothesis, the Fermi theory, and later developments in weak interaction physics. Covers the period from the late 1920s to the late 1950s, with emphasis on parity violation experiments. (A)
308. **"History of Weak Interactions,"** T. D. Lee, in *Elementary Processes at High Energy*, edited by A. Zichichi (Academic, New York, 1971), Part B, pp. 828–40. Reprinted in Ref. 99, Vol. 3, pp. 475–86. A sketch of the period 1930–56, concentrating on the τ-θ puzzle and the discovery of parity violation. (I)
309. **"The τ-θ Puzzle,"** R. H. Dalitz, in Ref. 47, pp. 332–48. Covers the history of the puzzle and the associated Lee–Yang hypothesis of parity violation, and "discusses also an alternative line of argument and experiment which might have been followed up at that time, and the possible reasons why physicists were so reluctant to embrace parity non-conservation." (A)
310. **"*K*-Meson Decays and Parity Violation,"** Richard H. Dalitz, in Ref. 39, pp. 434–57. Discusses the analysis of meson decays and the development of the τ-θ puzzle. (A)
311. **"Crucial Experiments on Discrete Symmetries,"** V. L. Telegdi, in Ref. 43, pp. 454–78. An experimenter's account of his and others' work on the P, C, and T symmetries during the period 1955–65. (A)
312. **"Discovery of Parity Violation in Weak Interactions,"** Chap. 3 of Ref. 68, γ Volume, pp. 93–162. Reprints the three famous experimental papers by C. S. Wu *et al.*, R. Garwin *et al.*, and J. I. Friedman and V. L. Telegdi. Includes discussions of parity violation by Lee and Yang and discussions of several experiments (led by R. T. Cox and C. T. Chase), performed around 1930, in which parity violation was apparently observed but not "discovered." (E)
313. **"Disproof of a Conservation Law,"** Chap. 10 of Ref. 69, pp. 155–77. On the history of parity, the experiments of 1956–57, and the "nondiscovery" experiments of the late 1920s. (E)
314. **"The Fall of Parity,"** Paul Forman, Phys. Teach. **20**, 281–88 (1982). "This article reproduces in altered form the label texts and illustrations of an exhibit with the same title at the National Museum of American History," Washington, DC. (E)
315. **"The Fall of Parity,"** Chap. 22 of *The New Ambidextrous Universe: Symmetry and Asymmetry from Mirror Reflections to Superstrings*, 3d rev. ed., Martin Gardner (Freeman, New York, 1990), pp. 211–22. An entertaining account by an accomplished science writer. "It is a pleasant thought that perhaps the familiar asymmetry of the Oriental [Yin–Yang] symbol, so much a part of Chinese culture, may have played a subtle, unconscious role in making it a bit easier for Lee and Yang to go against the grain of scientific orthodoxy, to propose a test which their more symmetric-minded Western colleagues had thought scarcely worth the effort." (E)
316. **"The Discovery and Nondiscovery of Parity Nonconservation,"** Allan Franklin, Stud. Hist. Philos. Sci. **10**, 201–57 (1979). Gives a detailed account of the theoretical prediction and experimental verification of parity violation around 1957 and compares the conditions surrounding the "crucial" experiments then with the state of affairs in the late 1920s and early 1930s, when parity violation—if scientists had recognized the implications of existing experimental results (reported by R. T. Cox *et al.* and C. T. Chase) supporting it—could in principle have been discovered. (See also Refs. 113 and 317.) (I)
317. **"The Nondiscovery of Parity Nonconservation,"** Allan Franklin, in Ref. 39, pp. 409–33. Summarizes part of Ref. 316. (I)
318. **"Justification of a 'Crucial' Experiment: Parity Nonconservation,"** Allan Franklin and Howard Smokler, Am. J. Phys. **49**, 109–12 (1981). Examines the 1957 evidence in favor of parity violation and concludes that the experiments were indeed "crucial" and that the physics community behaved "rationally." (See also Ref. 113.) (I)
319. **"Popper's Tetradic Schema, Progressive Research Programs, and the Case of Parity Violation in Elementary Particle Physics 1953–1958,"** Kostas Gavroglu, Zeitschrift für allgemeine Wissenschaftstheorie **16**, 261–86 (1985). A philosophically oriented study of the episode in relation to the views of Popper and Lakatos. (I)
320. **"Recent Evidence and Further Comments on Parity Violation,"** K. Gavroglu, Historia Sci. **31**, 115–23 (1986). Claims that Yang's recollections in Ref. 40, his commentary in Ref. 106 on his and Lee's famous theoretical paper of 1956, and Ref. 309 lend further support to the "preliminary conclusions" of Ref. 319, and makes additional observations on the methodology of physicists' approaches to resolving the τ-θ puzzle. (I)
321. **"Research Guiding Principles in Modern Physics: Case Studies in Elementary Particle Physics,"** Kostas Gavroglu, Zeitschrift für allgemeine Wissenschaftstheorie 7, 223–48 (1976). Applies a modification of Popper's "tetradic schema" in an attempt to account for the development of weak interaction theory after the emergence of the τ-θ puzzle. Also considers the manifestation of the "principle of contextual reinterpretation" in theorists' conception of discrete symmetries, in the research program of S. Sakata and M. Taketani on nuclear forces in the early 1950s and in the author's research program on nonleptonic weak decays of hyperons. (I)
322. **"Strong Inference and Weak Interactions,"** E. M. Hafner and Susan Presswood, Science **149**, 503–10 (1965). Discusses the interplay between theory and experiment in the history of weak interaction physics, focusing on the cases of P and CP violation. (I)
323. **"A Question of Parity: T. D. Lee and C. N. Yang,"** in *A Comprehensible World: On Modern Science and Its Origins,* Jeremy Bernstein (Random House, New York, 1967), pp. 35–73. First appeared in *The New Yorker*, 12 May 1962, pp. 49–104. An entertaining account of the lives and work of Lee and Yang, focusing on their role in the discovery of parity violation. (E)
324. **"Broken Parity,"** T. D. Lee, in Ref. 99, Vol. 3, pp. 487–509. Lee's account of his collaborations with Yang from 1946 until 1962, when they parted company for good. "Reluctantly and sadly I have to retrace the memory of a broken friendship." For Yang's perspective on their relationship, see Ref. 106, pp. 53–54. For additional details of their collaboration and breakup, see *Who Got Einstein's Office?: Eccentricity and Genius at the Institute for Advanced Study,* Ed Regis (Addison-Wesley, Reading, MA, 1987), pp. 140–47. (E)

See also Refs. 113, 114, and 328. A flurry of weak interaction research followed the discovery of parity violation. Work was done, in particular, on the two-component theory of the neutrino, which had previously been rejected because it would not conserve parity, and on the universal V–A theory, which naturally incorporated P asymmetry and was confirmed by diverse experiments as the correct form for the universal Fermi interaction.

325. **"Origin of the Universal V – A Theory,"** E. C. G. Sudarshan and R. E. Marshak, in Ref. 47, pp. 1–15. An account by two of the theory's formulators, focusing on the years 1947–59. (A)

Weak interaction physics from the early 50s onward has been the object of an intensive cliometric study by one group of researchers, who have examined patterns of article production, demography, and referencing by using an exhaustive bibliography of nearly 6000 serial articles published in the physics literature between 1950 and 1975.

326. **"The Weak Interactions from 1950 to 1960: A Quantitative Bibliometric Study of the Formation of a Field,"** D. Hywel White and Daniel Sullivan, in Ref. 39, pp. 390–406. Summarizes the background of the authors' bibliometric approach and focuses on "the events surrounding the emergence of the τ-θ puzzle, the discovery of parity nonconservation, and the resolution offered by the V–A theory." (I)

327. **"The State of a Science: Indicators in the Specialty of Weak Interactions,"** Daniel Sullivan, D. Hywel White, and Edward J. Barboni, Soc. Stud. Sci. 7, 167–200 (1977). An analysis of article production, demographic patterns, and referencing patterns in weak interaction physics during the period 1950–72, with "special attention to differences between theorists and experimentalists and to the impact of parity, V–A, and CP." (I)

328. **"The Interdependence of Theory and Experiment in Revolutionary Science: The Case of Parity Violation,"** D. Hywel White, Daniel Sullivan, and Edward J. Barboni, Soc. Stud. Sci. **9**, 303–27 (1979). Uses citation analysis to examine weak interaction physics between 1950 and 1972, in an attempt to assess Lakatos's ideas about the relationship between theory and experiment during "stagnating" and "progressive" periods in a scientific field, specifically, before, during, and after the discovery of parity nonconservation. (I)

329. **"Social Currents in Weak Interactions,"** D. Hywel White and Daniel Sullivan, Phys. Today **32** (4), 40–47 (1979). Uses citation analysis and ideas about scientific competition to study the controversy surrounding the possible violation of the $\Delta S = \Delta Q$ selection rule. Focuses on the years 1961–70. (E)

330. **"Problem Choice and the Sociology of Scientific Competition: An International Case Study in Particle Physics,"** Daniel Sullivan, Edward J. Barboni, and D. Hywel White, Knowledge and Society **3**, 163–97 (1981). Discusses the factors that have affected the problems chosen for attack by weak interaction physicists in different nations (the United States, the European countries, Russia, and Japan), with particular attention to the period 1964–66, during which CP nonconservation was first observed and "the temptation would have been great (if researchers select problems on the basis of their intrinsic interest) for physicists in weak interactions [in all countries] to be focused on the same set of problems." (I)

331. **"Understanding Rapid Theoretical Change in Particle Physics: A Month-by-Month Co-citation Analysis,"** D. Sullivan, D. Koester, D. H. White, and R. Kern, Scientometrics **2**, 309–19 (1980). Focuses on the weak–electromagnetic unification research program, 1971–75. (A)

332. **"Theory Selection in Particle Physics: A Quantitative Case Study of the Evolution of Weak–Electromagnetic Unification Theory,"** David Koester, Daniel Sullivan, and D. Hywel White, Soc. Stud. Sci. **12**, 73–100 (1982). Focuses on the period 1968–75 and on the interplay between theory and experiment. (I)

Apart from progress in weak interaction theory, which led to the later unification of the weak and electromagnetic forces, much theoretical work was done in the problematic realm of strong interaction physics, where new particles had been accumulating. In particular, dispersion relations, Regge analysis, and the "bootstrap" philosophy were employed in attempts to formulate a consistent theory of strongly interacting particles. The bootstrap model, worked on by Geoffrey Chew as a continuation of S-matrix theory, eschewed the quest for truly "elementary" particles and was much discussed as a controversial alternative to standard field theory. Equally controversial was the "Nagoya model" of elementary particles, worked out by Sakata and coworkers in 1959–60 and inspired by the dialectical materialism of Marx and Engels.

333. **"Particle Theory from S-Matrix to Quarks,"** Murray Gell-Mann, in Ref. 44, pp. 473–97. Reminiscences of developments in strong interaction theory, with discussion of the author's own contributions to dispersion relations, Yang–Mills theory, and early quark theory. Covers the period 1953–64. (I)

334. **"The History and Ideology of Dispersion Relations: The Pattern of Internal and External Factors in a Paradigmatic Shift,"** Marcello Cini, Fundam. Sci. **1**, 157–72 (1980). Examines the rise of the field of dispersion relations to paradigmatic status in 1955 and explains the sudden change of the field as a result of social factors particular to postwar America. "The dominant ideology in the U.S. lent itself particularly, through the mechanism of unbridled competitivity and the rat race, to the acceptance of a utilitarian and pragmatic, but fragmentary, concept of science with the consequent abandoning of its traditional aim of unification of knowledge." (I)

335. **"From Field Theory to Phenomenology: The History of Dispersion Relations,"** Andy Pickering, in Ref. 39, pp. 579–99. On the history of dispersion relations and the decline of quantum field theory in strong interaction physics of the 1950s. Argues, in agreement with Ref. 334, that the growth in phenomenological traditions was driven by social and economic factors. (See also Ref. 264.) (I)

336. **"The Importance of Heisenberg's S-Matrix Program for the Theoretical High-Energy Physics of the 1950s,"** James T. Cushing, Centaurus **29**, 110–49 (1986). A detailed history of S-matrix theory from Heisenberg's 1943 theory to the mid-1950s, with emphasis on the years 1947–55. (A)

337. **"Models and Methodologies in Current Theoretical High-Energy Physics,"** James T. Cushing, Synthese **50**, 5–101 (1982). A comprehensive, philosophically oriented conceptual history of the S-matrix theory and its predecessors. Covers the entire period 1900–1980. Applies Kuhn's and Lakatos's models of science to the two competing approaches of quantum field theory and S-matrix theory, and concludes that the cases are best interpreted in terms of the "progressive and degenerating problemshifts" of Lakatos's methodology of scientific research programmes. (I)

338. **"Theory Evaluation and the Bootstrap Hypothesis,"** Yehudah Freundlich, Stud. Hist. Philos. Sci. **11**, 267–77 (1980). Evaluates Chew's bootstrap program as an attempt to create a radically new physics, and covers the reception of the theory among particle physicists in the 1960s. (I)

339. **"Concrete versus Abstract Theoretical Models,"** Yuval Ne'eman, in *The Interaction Between Science and Philosophy*, edited by Y. Elkana (Humanities Press, Atlantic Highlands, NJ, 1974), pp. 1–25. A critical survey of philosophical components in strong interaction physics, including the bootstrap program and the Nagoya school, both of which are branded as "dogmatic." (A)

340. **"The Development of Elementary Particle Theory in Japan—Methodological Aspects of the Formation of the Sakata and Nagoya Models,"** Ziro Maki, in Ref. 66, pp. 83–95. A former student of Sakata explores the relationship between Sakata's scientific work and its underlying philosophical framework and discusses the Nagoya model of elementary particles. (A)

341. **"Hadron Symmetry, Classification and Compositeness,"** Yuval Ne'eman, in Ref. 44, pp. 501–40. A personal account of the author's involvement in strong interaction theory, 1955–62. Includes an autobiographical sketch. (I)

[*Authors' note:* For a detailed treatment of the S-matrix approach, see James T. Cushing's comprehensive historical and philosophical treatise *Theory Construction and Selection in Modern Physics: The S Matrix* (Cambridge U. P., New York, 1990), which appeared in print too late for enumeration in our manuscript.]

D. The "new physics" (1961–)

As it manifested itself in the science of particles, the "new physics" of the past three decades was initiated by two major theoretical developments in the 1960s: the quark conception of hadron structure and the Weinberg–Salam electroweak unification. The former led to the explanation of all matter in terms of two types of fundamental, apparently structureless units, quarks and leptons. The latter development led to the gauge theory "revolution," in which all the basic interactions between particles came to be seen as mediated by a small set of gauge fields. Beginning with the revitalization of the idea of gauge invariance by C. N. Yang and Robert Mills in 1954, (local) symmetry principles, through the gauge theories that incorporate them, eventually became elevated to paradigmatic status in modern physics. With the revival of field theory came the decline of the phenomenological and heuristic approaches that had spread through particle physics since the mid-50s. Broad treatments of elementary-particle theory during the period include:

342. **"Elementary Particles: Discovered or Constructed?"** Andrew Pickering, in *Physics in Collision: High-Energy ee/ep/pp Interactions,* Vol. 1, edited by W. Peter Trower and Gianpaolo Bellini (Plenum, New York, 1982), pp. 439–47. Sketches a wide range of developments in contemporary particle physics, while arguing that physicists do not passively discover facts of nature but "construct" them within theoretical and social contexts. (I)
343. **"An Exploratory Study of Kuhnian Paradigms in Theoretical High Energy Physics,"** Diana Crane, Soc. Stud. Sci. **10**, 23–54 (1980). Depends on interviews with 23 leading theorists to determine the principal lines of inquiry within elementary-particle theory during the years 1960–75, and argues that "theoretical innovations which give rise to new lines of inquiry in the field are performing roles analogous to those attributed by Kuhn to exemplars." Focuses on supersymmetry, the dual resonance model, and the Weinberg–Salam electroweak theory in a discussion of the nature of exemplars. (See also responses in the same volume: "Exemplars and Analogies: A Comment on Crane's Study of Kuhnian Paradigms in High Energy Physics," Andy Pickering, 497–502; "Reply to Pickering," Crane, 502–6; and "Reply to Crane," Pickering, 507–8.) (I)
344. **"The Methodology of Scientific Research Programmes and Some Developments in High Energy Physics,"** Kostas Gavroglu, in *Imre Lakatos and Theories of Scientific Change*, edited by Kostas Gavroglu, Yorgos Goudaroulis, and Pantelis Nicolacopoulos (Kluwer, Boston, 1989), pp. 123–33. "An attempt to critically appraise the basic claims of Imre Lakatos' epoch making paper ['Falsification and the Methodology of Scientific Research Programmes']...by testing them against some of the developments in elementary-particle physics" after 1965. Considers the rival metaphysical frameworks provided by quantum field theory, *S*-matrix theory, and their successors, gauge field theory and string theory. (I)

On the experimental side of the new physics, Big Science has become bigger. Over a hundred physicists, engineers, technicians, students, and administrators typically participate in different facets of a collider experiment of the contemporary era. Such cooperative efforts, involving teams of researchers from several institutions, may take years to plan and carry out. The structure of the high-energy physics community and especially the interactions between and within teams involved in modern, large-group experiments have been the focus of several exclusively sociological studies, which particularly illuminate the external factors that influence work in elementary-particle physics.

345. **Beamtimes and Lifetimes: The World of High Energy Physicists,** Sharon Traweek (Harvard U. P., Cambridge, MA, 1988). A cultural anthropologist's analysis of the particle physics community, based on five years of fieldwork at KEK, SLAC, and Fermilab. (E)
346. **Originality and Competition in Science: A Study of the British High Energy Physics Community,** Jerry Gaston (University of Chicago Press, Chicago, 1973). Looks at the organization, competition, and reward and communication system in British high-energy physics around 1970. Based on extensive interviews. (I)

Contemporary Big Science is surely epitomized by the SSC project, which—if there are no budgetary or engineering setbacks—will be constructed and begin operation by the year 2000. It will become the world's largest physics laboratory: The proton–proton collider's main ring will stretch over 50 miles underground on a 17 000-acre project site around Waxahachie, Texas; its 40-TeV total collision energy will be 20 times that of the now preeminent Fermilab Tevatron; it will require at least $8.25 billion to build and will eventually employ around 3000 people. This grand coalescence of government, academe, and industry goes forward to test the correctness of the gauge theories of the electroweak and strong forces, which have come together in the "standard model" of fundamental processes.

Preceding the proposal of the quark model was the development of the "eightfold way" hadronic classification scheme, based on the symmetry group flavor SU(3). Put forward independently by Murray Gell-Mann and Yuval Ne'eman early in 1961, this scheme at first faced competition from many others [including the Sakata model of elementary particles, which coworkers of Sakata reformulated in terms of SU(3)] and did not have much experimental grounding. But the discovery of the $\omega, \rho, \eta, K^*, \Sigma^*$, and Ξ^* particles and resonances in 1961–62 filled in gaps in the SU(3) multiplet arrangements, and the discovery of Gell-Mann's predicted Ω^- particle in 1964 clinched the viability of the eightfold way.

347. **"The Eightfold Way,"** Chap. 14 of Ref. 109, pp. 253–79. (E)
348. **"Discovery of Omega Meson—First Neutral Vector Meson,"** Chap. 3 of Ref. 68, ϵ Volume, pp. 77–112. Reprints the discovery paper and includes a personal account, by Bogdan Maglich, of the experiments that led to discovery of the first "heavy photon," the ω meson, in the new 72-inch hydrogen bubble chamber at LBL. (E)
349. **"Higher Symmetry for Elementary Particles,"** Chap. 15 of Ref. 69, pp. 265–81. On the eightfold way, its prediction of the Ω^-, and the discovery of the particle at BNL in 1964. (I)
350. **"Secretiveness and Competition for Priority of Discovery in Physics,"** Jerry Gaston, Minerva **9**, 472–92 (1971). Contains a sociohistorical account, based on interviews with unnamed "informants," of the race between American and European physicists to discover the Ω^-. (See also Ref. 346, pp. 83–93.) (E)

Gell-Mann and Ne'eman discuss their respective contributions in Refs. 333 and 341. On the bubble chamber experiments that found most of the particles and resonances that supported the eightfold way, see Ref. 468 and

351. **"Recent Developments in Particle Physics,"** Luis W. Alvarez, Science **165**, 1071–91 (1969); Ref. 52c, pp. 241–90; Ref. 53, pp. 1–49. Nobel lecture, delivered in Jan. 1969. (I)

In 1964 Gell-Mann and George Zweig independently proposed the quark hypothesis, based on the eightfold way. It met resistance at first, especially from advocates of the anti-field theoretic *S*-matrix approach and Chew's bootstrap program, who denied reductionistic explanation of hadrons in terms of more fundamental entities. And early attempts to detect free quarks failed; but one such experiment produced the antideuteron, which had long been expected to exist. Although since the 60 experimenters have occasionally claimed to have found isolated quarks, these results have never won wide acceptance.

352. **"The Quark Model,"** Chap. 4 of Ref. 110, pp. 85–124. Discusses the differences between the "constituent quark model" of Zweig and the "current algebra" approach of Gell-Mann, and comments on the traditions of theoretical, experimental, and phenomenological practice that the two formulations of the quark concept engendered through the late 1960s. (I)
353. **"Origins of the Quark Model,"** George Zweig, in *Baryon 1980: Proceedings of the IVth International Conference on Baryon Resonances* (1980), edited by Nathan Isgur (University of Toronto, Toronto,

n.d.), pp. 439–59. Provides "an intellectual history of the quark model prior to February 1964" and includes excerpts from many original sources. (A)

354. **"Search for Quarks Using 'Fermi Motion' and Discovery of the Antideuteron,"** Chap. 13 of Ref. 68, β 1972, pp. 291–320. Reprints papers from the quark search experiments at BNL in 1965, and contains Leon Lederman's personal account of the research, which readily uncovered the antideuteron but not an expectedly massive free quark. (E)

355. **The Hunting of the Quark: A True Story of Modern Physics,** Michael Riordan (Simon & Schuster/Touchstone, New York, 1987). A lively, semihistorical "detective story," based largely on the author's own experiences as an experimenter at SLAC during the late 1960s and early 1970s. Focuses on the search for quarks, 1964–79. (E)

356. **"The Hunting of the Quark,"** Andrew Pickering, Isis **72**, 216–36 (1981). Sketches the history of quark theory and searches, and then focuses on the development of and response to two contemporaneous search experiments (c. 1965–78), led by G. Morpurgo at the University of Genoa and by W. M. Fairbank at Stanford. Identifies the social structure, the experimental methods, and the "matrix of commitments" of the respective research groups as factors that contributed to the announcement of success by one group (Fairbank's), and failure by the other, in finding free quarks. (I)

357. **"Living in the Material World: On Realism and Experimental Practice,"** Andy Pickering, in *The Uses of Experiment: Studies in the Natural Sciences,* edited by David Gooding, Trevor Pinch, and Simon Schaffer (Cambridge U. P., New York, 1989), pp. 275–97. Uses a short, historical case study of G. Morpurgo's program of quark search experiments (1965–80) to illustrate the author's argument for a "pragmatic realist" perspective with regard to "the relation between articulated scientific knowledge and the material world." (I)

358. **"When Is a Particle?"** Sidney D. Drell, Phys. Today **31** (6), 23–32 (1978). Reprinted in Ref. 73, Vol. 2, pp. 851–68. Adapted version of the 1978 Richtmyer Memorial Lecture, published in Am. J. Phys. **46**, 597–606 (1978). Discusses the possible acceptance of the quark as an elementary constituent, in light of the evolving standards by which particles have been judged to be "elementary." Compares the case of the neutrino. (E)

359. **"Atomism in Crisis: An Analysis of the Current High Energy Paradigm,"** K. Shrader-Frechette, Philos. Sci. **44**, 409–40 (1977). Argues that elementary-particle physics is in a state of Kuhnian crisis and is in need of a new paradigm. Discusses "difficulties" of the quark model, and considers the bootstrap model as a possible alternative to the "fundamental particles" paradigm. (See Ref. 360 for an opposing view.) (I)

360. **"Atomism and the Illusion of Crisis: The Danger of Applying Kuhnian Categories to *Current* Particle Physics,"** R. E. Hendrick and Anthony Murphy, Philos. Sci. **48**, 454–68 (1981). A point-by-point criticism of Ref. 359, arguing that it is illegitimate to apply Kuhn's theory of science to current research. Discusses many discoveries of the 1970s that seem to support the elementary-particle view of matter. (I)

361. **"Simplicity and Observability: When Are Particles Elementary?"** Kostas Gavroglu, in *PSA 1988,* Vol. 1, edited by Arthur Fine and Jarrett Leplin (Philosophy of Science Association, East Lansing, MI, 1988), pp. 89–100. A primarily philosophical essay, focusing on the methodological role of "elementary" particles in the construction of theories. "Concerning the developments of the last 25 years, nowhere is this significance [of the conception of 'elementarity'] more pronounced than in the changes brought to the process followed for elementarizing the particles, and especially in specifying...procedures of observability. These procedures are not merely a convenient means for constructing theories...[but] also seem to be continually modifying the conceptual framework within which a series of philosophical and methodological issues of elementary particle physics are discussed." (I)

Broad histories of quark theory and experiment are given in Refs. 110 and 128.

Seven years after the P and C symmetries were discovered to be violated in the weak interactions, James W. Cronin, Val L. Fitch, James H. Christenson, and René Turlay observed that the combined symmetry CP was violated in the decay of the long-lived neutral kaon.

362. **"CP-Violation: The First 25 Years,"** Abraham Pais, in *CP Violation in Particle Physics and Astrophysics*, edited by J. Tran Thanh Van (Editions Frontières, Gif-sur-Yvette Cedex, France, 1990), pp. 3–35. A precise history of discrete symmetries and K-particle physics during the period 1946–70. Concentrates on the discovery of CP violation. (I)

363. **"The Discovery and Acceptance of CP Violation,"** Allan Franklin, Hist. Stud. Phys. Sci. **13**, 207–38 (1983). Examines the historical background, organization, and reception of the "crucial" experiment of Cronin *et al.* Includes a discussion of alternative explanations of the experiment that were offered but not taken seriously between 1964 and 1970. (See also Ref. 113.) (I)

364. **"The Response to Crisis—A Contemporary Case Study,"** T. P. Swetman, Am. J. Phys. **39**, 1320–28 (1971). Examines the response of the physics community to the 1964 evidence in favor of CP violation and concludes that Kuhn's paradigm theory applies to the episode. (I)

365. **"CP Symmetry Violation,"** James W. Cronin and Margaret S. Greenwood, Phys. Today **35**(7), 38–44 (1982). An informal account of the discovery and implications of CP asymmetry. (E)

366. **"The Discovery of Charge-Conjugation Parity Asymmetry,"** Val L. Fitch, Science **212**, 989–93 (1981); Rev. Mod. Phys. **53**, 367–71 (1981). Nobel lecture, delivered in Dec. 1980. (I)

367. **"CP Symmetry Violation: The Search for Its Origin,"** James W. Cronin, Science **212**, 1221–28 (1981); Rev. Mod. Phys. **53**, 373–83 (1981). Nobel lecture, delivered in Dec. 1980. (A)

See also Refs. 113, 311, 322, and 330. The violation of P, CP, and C has been well characterized through many experiments, and today only the combination CPT is believed to be an exact symmetry.

Through the early 1960s, physicists became increasingly pessimistic about the prospect of achieving a successful quantum field theory of the weak and especially of the strong interaction. Although the V–A theory accounted for most weak interaction phenomena, it proved not to be renormalizable by any procedure analogous to the one used in QED. Although the Yang–Mills theory of 1954 had been proposed as a gauge-symmetric field theory of the strong interaction, the quanta of the Yang–Mills gauge field had to be massless, and the theory could not, therefore, account for the short range of the nuclear forces; modifying the original Yang–Mills theory by endowing its gauge bosons with mass produced nonrenormalizable infinities. As late as 1965, Freeman Dyson wrote in *Physics Today,* "It is easy to imagine that in a few years the concepts of field theory will drop totally out of the vocabulary of day-to-day work in high-energy physics." However, while skepticism grew with regard to the applicability and fundamentality of local gauge theories, the seeds were sown for the revival of the Yang–Mills approach. Specifically, in the early 1960s the concept of spontaneous symmetry breaking, which had been explored in various physical contexts in the first decades of the century, was "rediscovered" in the Bardeen–Cooper–Schrieffer theory of superconductivity (1957) and integrated into quantum field theory by Yoichiro Nambu, Jeffrey Goldstone, and others. In 1964 the Higgs mechanism of spontaneous symmetry breaking was introduced by Peter Higgs and by François Englert and Robert Brout, and this technique offered a means of endowing the Yang–Mills (charged) fields with mass while preserving the exact gauge symmetry of the theory. The Higgs mechanism soon became a fundamental ingredient in the Weinberg–Salam electroweak unification.

368. **"Gauge Fields,"** Robert Mills, Am. J. Phys. **57**, 493–507 (1989). An informal survey of the history and ideas of gauge theory, from the pioneering work of E. Noether, H. Weyl, and F. London in the 1910s and 1920s to the ongoing attempts to formulate a "theory of everything." (I)

369. **"Gauge Field Theories,"** M. Veltman, in *Proceedings of the 6th International Symposium on Electron and Photon Interactions at High Energies* (1973), edited by H. Rollnik and W. Pfeil (North-Holland, New York, 1974), pp. 429–47. Includes a brief section entitled "Historical Review and Bibliography" (pp. 439–43), which surveys the principal contributions to gauge field theory from the pioneering work of Yang and Mills to the work of Weinberg, DeWitt, 't Hooft, and others. (A)

370. **"Gauge Theories of the Forces Between Elementary Particles,"** Gerard 't Hooft, Sci. Am. **242** (6), 104–38 (June 1980). Reprinted in Ref. 71, pp. 78–105. A semihistorical treatment of the rise to prominence of non-Abelian gauge theories with local symmetry, by the theorist who proved the renormalizability of spontaneously broken gauge theories in 1971 and thus spurred unification efforts. (E)

371. **"Gauge Theory and the Geometrization of Fundamental Physics,"** Tian-Yu Cao, in *Philosophical Foundations of Quantum Field Theory*, edited by Harvey R. Brown and Rom Harré (Oxford U. P., New York, 1988), pp. 117–33. Discusses the geometrical interpretation of nongravitational gauge interactions, with semihistorical attention to the development of the fiber bundle version of gauge theory, supersymmetry and supergravity, modern Kaluza–Klein theory, and superstring theory. Includes a brief history of the idea of gauge invariance (originated by Weyl in 1918) and the emergence of modern gauge theory (begun by Yang and Mills in 1954) within quantum field theory. (A)

372. **"Symmetry and Spontaneously Broken Symmetry in the Physics of Elementary Particles,"** Philip D. Mannheim, in *Symmetry: Unifying Human Understanding* [Computers and Math. with Applications **12** B (1986)], edited by István Hargittai (Pergamon, New York, 1986), pp. 169–83. A historical survey of the role of symmetry in the history of elementary-particle physics. (I)

373. **"Spontaneous Breakdown of Symmetry: Its Rediscovery and Integration into Quantum Field Theory,"** Laurie M. Brown and Tian Yu Cao, Hist. Stud. Phys. Biol. Sci. **21**, (211–36) (1991). Sketches the history of the concept of spontaneous symmetry breaking from the late 1800s to the mid-1950s; focuses on the incorporation of that concept into quantum field theory via the contributions of the BCS theory of superconductivity, Heisenberg's concept of a degenerate vacuum and his nonlinear field theory, and Nambu's analogy between superconductivity theory and field theory; and surveys the "final integration" of spontaneous symmetry breaking into quantum field theory through the work of Goldstone, M. Baker, S. Glashow, and P. W. Anderson in the early 1960s. (A)

374. **"SBGT and All That,"** Peter Higgs, in Ref. 47, pp. 168–72. A personal account of the author's work on spontaneously broken gauge theories, 1961–67. (I)

Many essays in Ref. 44 also treat the historical role of symmetry as a guiding force in physics.

In 1967–68 Steven Weinberg and Abdus Salam independently proposed a unified theory of the weak and electromagnetic interactions based on a spontaneously broken gauge symmetry $SU(2)_L \times U(1)$. Sheldon Glashow had earlier made significant contributions toward such a unification. The Weinberg–Salam theory was ignored until late 1971, when Gerard 't Hooft demonstrated that Yang–Mills theories incorporating the Higgs mechanism are renormalizable. The confirmation of the renormalizability of the electroweak theory brought to an end the "dark age" of gauge theory.

375. **"The 1979 Nobel Prize in Physics,"** Sidney Coleman, Science **206**, 1290–92 (1979). A theoretical physicist's summary of Glashow, Weinberg, and Salam's contributions to electroweak unification. Claims that this development fits Kuhn's model of anomaly, crisis, and revolution "almost perfectly." (E)

376. **"Conceptual Foundations of the Unified Theory of Weak and Electromagnetic Interactions,"** Steven Weinberg, Science **210**, 1212–18 (1980); Rev. Mod. Phys. **52**, 515–23 (1980); Ref. 73, Vol. 3, pp. 153–68; Ref. 92, pp. 1–8. Nobel lecture, delivered in Dec. 1979. (E)

377. **"Toward a Unified Theory: Threads in a Tapestry,"** Sheldon L. Glashow, Science **210**, 1319–23 (1980); Rev. Mod. Phys. **52**, 539–43 (1980); Ref. 73, Vol. 3, pp. 193–203; Ref. 92, pp. 23–27. Nobel lecture, delivered in Dec. 1979. (E)

378. **"Gauge Unification of Fundamental Forces,"** Abdus Salam, Science **210**, 723–32 (1980); Rev. Mod. Phys. **52**, 525–38 (1980); Ref. 73, Vol. 3, pp. 171–90 (abridgment); Ref. 92, pp. 9–22; Ref. 494, pp. 375–90. Nobel lecture, delivered in Dec. 1979. (I)

379. **"The Unification of Electromagnetism with the Weak Force,"** Paul Langacker and Alfred K. Mann, Phys. Today **42** (12), 22–31 (1989). A sketch of the history of the electroweak theory and its experimental testing. (I)

380. **"Electroweak Unification and the Appraisal of Theories,"** Michael J. Hones, in *Scrutinizing Science: Empirical Studies of Scientific Change*, edited by Arthur Donovan, Larry Laudan, and Rachel Laudan (Kluwer, Boston, 1988), pp. 359–75. Uses the development of the electroweak unification program within the context of QED, 1970–73, to test theses about theory appraisal, and concludes that the empirical appraisal of a theory depends on "phenomena which can be detected and measured without using assumptions drawn from the theory under evaluation" and depends on "its ability to solve the largest number of empirical problems." Briefly reviews the history of the V–A theory and Yang–Mills theories. (I)

See also Refs. 331 and 332. Over the decade 1973–83, experiments confirmed several predictions of the electroweak theory. The first significant support came from the discovery of neutral currents in neutrino reactions in 1973.

381. **"How the First Neutral Current Experiments Ended,"** Peter Galison, Rev. Mod. Phys. **55**, 477–509 (1983). A historical examination and comparison of the "Gargamelle" experiment at CERN and "E1A" at Fermilab. Looks at "the organization of the experiments, the nature of the apparatus, and the previous work of the experimentalists." (I)

382. **"Ending a High-Energy Physics Experiment,"** Chap. 4 of Ref. 112, pp. 135–241. A more detailed version of Ref. 381, focusing on the experimenters' theoretical assumptions, experimental techniques, social dynamics, and individual research styles in order "to depict the process by which experimental evidence becomes convincing." (I)

383. **"The Discovery of Neutral Currents,"** Peter Galison, in Ref. 47, pp. 349–91. A summary of Ref. 381, with comments on the historiographical interests that are elaborated in Ref. 112. (I)

384. **"Against Putting the Phenomena First: The Discovery of the Weak Neutral Current,"** Andrew Pickering, Stud. Hist. Philos. Sci. **15**, 85–117 (1984). Reviews the experiments that discovered neutral currents, and their background from approaches to weak interaction physics in the 1960s. Argues that a "symbiotic relationship between experimenters and theorists" encouraged the physicists' acceptance of the existence of the weak neutral current "because they could see how to ply their trade more profitably in a world in which the neutral current was real." (For criticism of this view, see Ref. 112.) (I)

385. **"Editing and Epistemology: Three Accounts of the Discovery of the Weak Neutral Current,"** Andrew Pickering, Knowledge and Society **8**, 217–32 (1989). Compares a scientist's "popular" account [in *The Cosmic Onion: Quarks and the Nature of the Universe*, Frank Close (Heinemann, London, 1983)] of the discovery at Gargamelle, P. Galison's "historical" account in Ref. 381, and the author's own "constructivist" account in Ref. 384, and argues that the "realist epistemology" characteristic of scientific popularizations and academic histories of science is "unstable and ultimately untenable" for the purpose of historical explanation, whereas "a conventionalist and constructivist epistemology...appears to be historiographically stable." (I)

386. **"The Neutral-Weak-Current Experiments: A Philosophical Perspective,"** Michael J. Hones, Stud. Hist. Philos. Sci. **18**, 221–51 (1987). Summarizes the experiments that discovered weak neutral currents and argues that this work can be described by a modification of L. Laudan's "reticulated model of scientific rationality," combined with the sociological description of Ref. 384. (I)
387. **"An Experimenter's History of Neutral Currents,"** F. Sciulli, Prog. Part. Nucl. Phys. **2**, 41–87 (1979). A technical review giving the motivations for and descriptions of over a dozen experiments to detect and explore the properties of neutral currents between 1972 and 1977. (A)
388. **"The Detection of Neutral Weak Currents,"** David B. Cline, Alfred K. Mann, and Carlo Rubbia, Sci. Am. **231** (6), 108–19 (1974). An excellent description of the Fermilab experiments. (E)

See also Ref. 114, Chap. 8.

Closely modeled on QED, quantum chromodynamics (QCD)—a gauge theory of the strong interactions among quarks, based on the symmetry group color SU(3)—was developed in the mid-1970s, by which time experimental evidence had convinced most physicists that quarks were "real" entities and not mere mathematical artifacts. Fundamental to the rise of QCD was its implication of "asymptotic freedom." This property of the theory was discovered by David Gross and Frank Wilczek and by David Politzer in 1973 and lent support to the idea that quarks are permanently confined within hadrons, which could explain the many failures to detect bare quark charges.

389. **"The Confinement of Quarks,"** Yoichiro Nambu, Sci. Am. **235** (5), 48–60 (1976). A semihistorical account of quark theory and QCD by one of the founders of QCD. (E)
390. **"How Asymptotic Freedom Discovered Me,"** in *Longing for the Harmonies: Themes and Variations from Modern Physics,* Frank Wilczek and Betsy Devine (Norton, New York, 1988), pp. 207–17. (E)

Shortly before 't Hooft had proved the renormalizability of spontaneously broken gauge theories and thereby sparked interest in the Weinberg–Salam theory, Glashow and two colleagues, in attempting to explain the weak interactions of hadrons, had introduced a fourth quark, the "charmed" quark (c), into the existing theory containing the "up" (u), "down" (d), and "strange" (s) quarks. Because invoking this new particle explained (by design) the apparent absence of strangeness-changing neutral currents in nature, the GIM (Glashow–Iliopoulos–Maiani) mechanism eventually became associated with the Weinberg–Salam theory. The new quark flavor implied the existence of new families of mesons and baryons. After the J/ψ resonance was discovered in November 1974 in independent experiments led by Samuel Ting at BNL and Burton Richter at SLAC, the new particle (called J by the MIT–BNL team and ψ by the SLAC–LBL team) was soon interpreted as a (bound) $c\bar{c}$ state (generically dubbed "charmonium"), that is, as a meson with "hidden" charm. By mid-1976, discoveries of other states of charmonium and of other charmed mesons (e.g., D^0 [$c\bar{u}$] and D^+ [$c\bar{d}$]—"naked"-charm states) had firmly established the charm scheme. The announcement of the J/ψ became known as the "November revolution," for in its aftermath charm was confirmed and the Weinberg–Salam and GIM theories were joined into the "standard model" of electroweak interactions.

391. **"Discovery of Massive Neutral Vector Mesons,"** Chap. 4 of Ref. 68, ϵ Volume, pp. 113–65. Reprints the papers announcing the discoveries of the J/ψ and ψ', and includes personal accounts of the research by G. Goldhaber, B. Richter, and S. Ting. (E)
392. **"The Discovery of the J Particle: A Personal Recollection,"** Samuel C. C. Ting, Science **196**, 1167–78 (1977); Rev. Mod. Phys. **49**, 235–49 (1977). Nobel lecture, delivered in Dec. 1976. (I)
393. **"From the Psi to Charm: The Experiments of 1975 and 1976,"** Burton Richter, Science **196**, 1286–97 (1977); Rev. Mod. Phys. **49**, 251–66 (1977). Nobel lecture, delivered in Dec. 1976. (I)
394. **"Fundamental Particles with Charm,"** Roy F. Schwitters, Sci. Am. **237** (4), 56–70 (1977). A semihistorical account, by a member of the SLAC–LBL collaboration, of the experiments (1974–76) that found the J/ψ and other charmed mesons. (E)
395. **"The Role of Interests in High-Energy Physics: The Choice Between Charm and Colour,"** Andrew Pickering, in *The Social Process of Scientific Investigation*, edited by Karin D. Knorr, Roger Krohn, and Richard Whitley (Reidel, Boston, 1980), pp. 107–38. A sociological analysis of the adoption of the "charm" model and the rejection of its competitor, "color," in light of the discoveries of the J/ψ and its relatives, during the period 1974–76. (I)
396. **"Charm Revisited: A Quantitative Analysis of the HEP Literature,"** Andy Pickering and Edward Nadel, Soc. Stud. Sci. **17**, 87–113 (1987). Uses citation analysis to study the development of the charm model, 1974–77. (I)
397. **"Quarkonium,"** Elliot D. Bloom and Gary J. Feldman, Sci. Am. **246** (5), 66–77 (1982). Reprinted in Ref. 70, pp. 145–64. Includes a description of discoveries of charmonium states at SLAC and DESY through 1981. (E)
398. **"High-Energy Models and the Ontological Status of the Quark,"** K. S. Shrader-Frechette, Synthese **42**, 173–89 (1979). Argues that although the discovery of charm gives support to the existence of quarks, it challenges their status as elementary constituents. (I)

With the institution of charm, the number of quarks matched the number of leptons. But the appealing correspondence $(u, d, s, c) \Leftrightarrow (e^-, \nu_e, \mu^-, \nu_\mu)$ was short-lived, for in 1975 Martin Perl and coworkers at SLAC announced their discovery of a new, heavy lepton, the τ.

399. **"Confirmation with Technology: The Discovery of the Tau Lepton,"** Jonathan Treitel, Centaurus **30**, 140–80 (1987). An account of the search for and detection of the τ at SLAC during the early and mid-1970s. Argues that the confirmation of the τ was accomplished via a "methodology of confirmation," or "confirmology," which was associated with a "scientific program" [analogous to a "paradigm" (Kuhn), "research programme" (Lakatos), or "research tradition" (Laudan)], which was a fusion of two separate programs associated with research groups (from LBL and SLAC) that came together in the τ search. (I)
400. **"Confirmation as Competition: The Necessity for Dummy Rival Hypotheses,"** Jonathan Treitel, Stud. Hist. Philos. Sci. **18**, 517–25 (1987). A philosophical analysis of the τ discovery. Argues that scientists' belief that the τ had actually been detected solidified only after "dummy rival hypotheses"—alternatives to a preferred hypothesis that are manufactured solely for the purpose of demonstrating their inferiority—were put forward and refuted. (I)
401. **"Heavy Leptons,"** Martin L. Perl and William T. Kirk, Sci. Am. **238** (3), 50–57 (1978). Reprinted in Ref. 70, pp. 99–111. (E)

In experiments performed at Fermilab in 1975–78 by Leon Lederman and colleagues, a family of Υ resonances was discovered. In analogy with the interpretation of the J/ψ, the new, massive particle was immediately held to indicate the existence of a fifth, massive quark, called "bottom" or "beauty" (b); the Υ resonances were (bound) $b\bar{b}$ states, "bottomonium." Subsequently, naked bottom was observed in B mesons produced at Cornell University's CESR facility. The discovery of the new quark flavor thus restored a symmetrical arrangement of the fundamental particles, an arrangement having both a third generation of leptons and (apparently) a third generation of quarks (and recent evidence, from measurements of the Z^0 lifetime, seems to limit the number of generations to three). Using the Tevatron and the Collider Detector at Fermilab, physicists continue to hunt the sixth quark, called "top" or "truth" (t), which must be at least 18 times more massive than the b.

402. **"The Upsilon Particle,"** Leon M. Lederman, Sci. Am. **239** (4), 72–80 (1978). Reprinted in Ref. 70, pp. 129–44. (E)

403. **"Particles with Naked Beauty,"** Nariman B. Mistry, Ronald A. Poling, and Edward H. Thorndike, Sci. Am. **249** (1), 106–15 (1983). Reprinted in Ref. 70, pp. 165–80. An account of b-quark experiments performed at Cornell University beginning in late 1979. (E)

In the mid-1970s the first "grand unified theories" (GUTs) of the strong, weak, and electromagnetic interactions were proposed. The theory of Howard Georgi and Sheldon Glashow, based on the symmetry group SU(5), emerged as the prototype for many unification efforts. Two predictions of most GUTs were the nonconservation of baryon number and the existence of very massive magnetic monopoles. Monopoles had been an object of speculation for many years (see Refs. 219–22). Around the same time that GUTs began to be developed, some researchers claimed to have discovered a monopole in a high-altitude cosmic-ray experiment, but that interpretation of their particle track was widely criticized and quickly dismissed, and theorists soon pointed out that the monopoles required by gauge theories would be much more massive than any particles yet detected. A more convincing monopole candidate was observed by Stanford University physicist Blas Cabrera on St. Valentine's Day in 1982, but the discovery was not confirmed.

404. **"The Decay of the Proton,"** Steven Weinberg, Sci. Am. **244** (6), 64–75 (June 1981). Reprinted in Ref. 71, pp. 109–23. Surveys the theory of proton decay and the experiments to test it. (E)

405. **"The Search for Proton Decay,"** J. M. LoSecco, Frederick Reines, and Daniel Sinclair, Sci. Am. **252** (6), 54–62 (1985). Reprinted in Ref. 71, pp. 124–35. Surveys experimental techniques used in searches for proton decay, and focuses on the Irvine–Michigan–Brookhaven experiment (in which the authors were involved) at the Morton salt mine near Cleveland, Ohio. (E)

406. **"Waiting for the Proton to Decay,"** Lawrence R. Sulak, Am. Scientist **70**, 616–25 (1982). A physicist's account of experiments to detect proton decay, focusing on the Irvine–Michigan–Brookhaven experiment. Includes a "historical perspective" that looks at the law of baryon conservation, proposed by Weyl (1929), Stückelberg (1939), and Wigner (1949). (E)

407. **"Constraints on Controversy: The Case of the Magnetic Monopole,"** Andrew Pickering, Soc. Stud. Sci. **11**, 63–93 (1981). Studies the controversy in experimental physics that followed the claimed observation of a magnetic monopole by P. B. Price, E. K. Shirk, W. Z. Osborne, and L. S. Pinsky in 1975. (On this controversy see also Ref. 220.) (I)

408. **"Superheavy Magnetic Monopoles,"** Richard A. Carrigan, Jr., and W. Peter Trower, Sci. Am. **246** (4), 106–18 (1982). Reprinted in Ref. 71, pp. 136–47. Reviews the magnetic monopole conjecture, including the very massive 't Hooft–Polyakov monopoles proposed in the mid-1970s, and surveys various searches for monopoles, including Price and team's purportedly successful one. (E)

A central calculation of GUTs—the extremely high "grand unification mass" (energy) at which the strong, weak, and electromagnetic forces would be equal and unseparated and at which hypothetical X and Y bosons, carriers of the force through which quarks can change into leptons or antiquarks (and thereby cause proton decay), would be produced—spurred the linking of elementary-particle physics with cosmology, for an energy of this magnitude is far beyond the reach of particle accelerators and would have been produced only in the Big Bang. The most important event in this disciplinary interface was Alan Guth's proposal, in 1980, of the inflationary universe model, which evolved into the "new" inflationary model under modifications developed independently by A. D. Linde and by Paul Steinhardt and Andreas Albrecht in 1981.

409. **"The Early Universe and High-Energy Physics,"** David N. Schramm, Phys. Today **36** (4), 27–33 (1983). Reprinted in *Astrophysics Today* (see Ref. 187), pp. 323–29. (E)

410. **"Cosmology, Astrophysics and Elementary Particle Physics,"** R. J. Tayler, Reports on Progress in Phys. **43**, 253–99 (1980). A detailed treatment, including references to older theories and experiments. (A)

411. **"The Cosmic Burp: The Genesis of the Inflationary Universe Hypothesis,"** Marcia Bartusiak, Mercury **16**, 34–45 (1987). Adapted from *Thursday's Universe* (Times Books, New York, 1986), Chap. 10. A popular account. (E)

412. **"The Inflationary Universe,"** Alan H. Guth and Paul J. Steinhardt, Sci. Am. **250** (5), 116–28 (1984). Reprinted in Ref. 71, pp. 178–96, and in Ref. 73, Vol. 3, pp. 321–48. A more elaborate version of this article appears in *The New Physics*, edited by Paul Davies (Cambridge U. P., New York, 1989), pp. 34–60. (E)

In 1983 the discovery of the intermediate vector bosons W^+, W^-, and Z^0—mediators of the weak force—by Carlo Rubbia, Simon van der Meer, and team at CERN finally guaranteed the viability of the Weinberg–Salam electroweak theory, which had predicted the particles.

413. **Story of the W and Z,** Peter Watkins (Cambridge U. P., New York, 1986). A popularization of theoretical and experimental developments that led to the prediction and subsequent discovery of the W and Z bosons. Focuses on the UA1 experiment, in which the author participated. (E)

414. **The Particle Connection: The Most Exciting Scientific Chase Since DNA and the Double Helix,** Christine Sutton (Simon and Schuster, New York, 1984). A physicist's popular account of the discovery and significance of the W and Z. (E)

415. **Nobel Dreams: Power, Deceit and the Ultimate Experiment,** Gary Taubes (Random House, New York, 1986). An adventurous look at Rubbia's work in confirming the W and Z, and his subsequent efforts to identify experimental support for supersymmetry. (E)

416. **"The Discovery of the Intermediate Vector Bosons,"** Anne Kernan, Am. Scientist **74**, 21–28 (1986). An experimental physicist's summary of the UA1 experiment and its background. (E)

417. **"The Search for Intermediate Vector Bosons,"** David B. Cline, Carlo Rubbia, and Simon van der Meer, Sci. Am. **246** (3), 48–59 (1982). Reprinted in Ref. 70, pp. 112–26. (E)

418. **"Experimental Observation of the Intermediate Vector Bosons W^+, W^-, and Z^0,"** Carlo Rubbia, Rev. Mod. Phys. **57**, 699–722 (1985). Nobel lecture, delivered in Dec. 1984. (I)

The extension of unification to encompass the gravitational force has long been a seemingly insurmountable difficulty in elementary-particle theory. The most impressive advances toward a "totally unified theory" (TUT), or "theory of everything" (TOE), have come through the recent revival and extension of string theory, which was originally developed in strong interaction physics of the late 60s and early 70s but was virtually abandoned after the introduction of QCD. The incorporation of the supersymmetry and supergravity components of many GUTs into a supersymmetric string theory was pioneered by Michael Green and John Schwartz in the early 80s. Although superstring theory appears to provide a consistent quantum theory of gravity and has become a locus of intense research in physics and mathematics, at present the theory is far from mature, and its elegant mathematical development has yet to yield verifiable experimental predictions.

419. **"Superstrings,"** Michael B. Green, Sci. Am. **255** (3), 48–60 (1986). Reprinted in Ref. 70, pp. 183–203. Traces the conceptual development of superstring theory, beginning with its roots in the "dual resonance model" of the late 1960s. (E)

420. **"From the Bootstrap to Superstrings,"** John H. Schwartz, in Ref. 55, pp. 106–13. "The historical roots of superstring theory in the hadronic bootstrap and Regge-pole theory are recalled. Recent developments in superstring theory are then summarized." (A)

421. **Superstrings: A Theory of Everything?** edited by P. C. W. Davies and Julian Brown (Cambridge U. P., New York, 1988). Based on a BBC radio documentary. Contains interviews, often including historical comments, with leading proponents (e.g., M. Green, J. Schwartz, and E. Witten) and critics (e.g., R. Feynman and S. Glashow) of string theory. (E)

See also Ref. 422. Since the mid-1960s another "beautiful" theory, a nonlocal theory of space-time based on abstract geometrical objects known as "twistors," has been developed and applied to the description of elementary particles by the British mathematician and physicist Roger Penrose and colleagues. In the more popular superstring theory, the fundamental entities in nature are postulated to be strings of length on the order of the Planck length ($\simeq 10^{-35}$ m), and both matter and space are interpreted as manifestations of these extended strings; in twistor theory, the fundamental entities are taken to be the geometric structures in twistor space (specifically, in projective twistor space, a complex three-dimensional vector space), from which one attempts to build the points of space-time and the particles of matter. Like superstrings, twistor theory is incomplete and not yet testable by experiment, but some physicists are hopeful that the twistor and superstring approaches might be combined into a deeper theory that will provide a unified explanation of all of the basic forces of nature.

422. **Superstrings and the Search for the Theory of Everything,** F. David Peat (Contemporary Books, Chicago, 1988). A popular, semihistorical survey of superstring theory and twistor theory. (E)

423. **"On the Origins of Twistor Theory,"** Roger Penrose, in *Gravitation and Geometry: A Volume in Honour of Ivor Robinson,* edited by Wolfgang Rindler and Andrzej Trautman (Bibliopolis, Naples, 1987), pp. 341–61. "Personal or technical reminiscences" on the considerations that motivated the author's twistor approach to physical theory. "This viewpoint has guided us in certain unexpected and often fruitful directions.... Nevertheless, twistors do *not*, as yet, provide a new physical theory in the usual sense that predictions different from those given by conventional procedures are yet forthcoming." (I)

VII. HISTORIES OF INSTRUMENTS, INSTITUTIONS, AND CONFERENCES

In addition to the references listed below, Refs. 48 and 49 contain many valuable essays on the history of various laboratories, instruments, and experimental techniques.

A. General works

424. **Particle Accelerators: A Brief History,** M. Stanley Livingston (Harvard U. P., Cambridge, MA, 1969). Largely based on lectures delivered at Harvard University, 1967–68. Presents "facets of accelerator history as experienced and observed by the author" from the early 1930s to the late 1960s. (E)

425. **The Development of High Energy Accelerators,** edited by M. Stanley Livingston (Dover, New York, 1966). Reprints 28 important scientific papers dealing with the development of accelerators, from Van de Graff's electrostatic generator of 1931 to the 6-GeV Cambridge electron accelerator of 1961. (A)

426. **"Early History of Particle Accelerators,"** M. Stanley Livingston, Advances in Electronics and Electron Phys. **50**, 1–88 (1980). Begins with the experiments of J. W. Hittorf and others (c. 1870) on electrical discharge in gases and proceeds to discuss direct voltage accelerators, resonance acceleration, the betatron, synchronous accelerators, linear accelerators, alternating gradient accelerators, and storage rings and colliding beams. (A)

427. **"Particle Accelerators,"** E. M. McMillan, in *Experimental Nuclear Physics*, Vol. 3, edited by E. Segrè (Wiley, New York, 1959), pp. 639–785. Describes accelerators built from the late 1920s through the early 1950s. Contains numerous references and pictures. Section 1 (pp. 639–57) details "Early History, 1926–1933." (A)

428. **"U.S. Particle Accelerators at Age 50,"** R. R. Wilson, Phys. Today **34** (11), 86–103 (1981). A nontechnical survey of the development of American accelerator physics, 1930–80. (E)

429. **"Early History of Particle Accelerators,"** Edwin M. McMillan, in Ref. 171, pp. 113–47. Covers the development of accelerators up to 1932. Includes an appendix of 15 letters, in which pioneers of accelerator physics (McMillan, M. A. Tuve, E. T. S. Walton, and others) discuss the earliest history of their field. (I)

430. **"The History of the Development of the Cyclotron Over Fifty Years (1930–1980),"** L. M. Nemenov, Sov. Phys. Usp. **24**, 231–40 (1981). Emphasizes Soviet contributions. (I)

431. **"A History of the Synchrotron,"** Edwin M. McMillan, Phys. Today **37** (2), 31–37 (1984). Based on a Morris Loeb Lecture presented at Harvard University in April 1982. An account of "the events surrounding the origin of the synchrotron—the machine that made high-energy physics possible—narrated by a discoverer of the phase-stability principle that made the synchrotron possible." Covers the years 1945–48. (E)

432. **"Basic Research in the East and West—A Comparison of the Scientific Performance of High-Energy Physics Accelerators,"** Benjamin R. Martin and John Irvine, Soc. Stud. Sci. **15**, 293–341 (1985). A comparative evaluation of Japanese and American accelerator physics, mainly during the 1970s, based on quantitative data such as citation frequency. Focuses on scientometric techniques as a basis for formulating science policy. (I)

433. **"Internal Criteria for Scientific Choice: An Evaluation of Research in High-Energy Physics Using Electron Accelerators,"** Benjamin R. Martin and John Irvine, Minerva **19**, 408–32 (1981). A science policy assessment of the quality and impact of research at the NINA electron synchrotron in Daresbury, England, compared with research at SLAC (Stanford), DESY (Hamburg), and CEA (Cambridge, MA). Uses data for the 1960s and 1970s. (I)

B. European Organization for Nuclear Research (CERN)

434. **The Big Machine,** Robert Jungk (Scribner's, New York, 1968). A popular treatment of accelerators and their builders and operators, with a focus on CERN. (E)

435. **History of CERN,** 2 vols., Armin Hermann, John Krige, Dominique Pestre, and Ulrike Mersits (North-Holland, New York, 1987 and 1990). Volume 1, *Launching the European Organization for Nuclear Research*, provides detailed coverage of CERN's prehistory and history from 1949 to 1954; sections focus on the postwar emergence of high-energy physics, the scientific and administrative planning of the laboratory, and the political difficulties that arose in uniting European nations in a large-scale effort. Volume 2, *Building and Running the Laboratory*, continues the history through the mid-1960s; sections focus on the construction and exploitation of the 600-MeV synchrocyclotron and the 28-GeV proton synchrotron, and the planning and management of research. (I)

436. **"Arguments Pro and Contra the European Laboratory in the Participating Countries,"** Armin Hermann, in Ref. 39, pp. 519–24. A summary of the process by which England, France, Italy, and Germany decided to join CERN in 1954. (E)

437. **"Why Did Britain Join CERN?"** John Krige, in *The Uses of Experiment* (see Ref. 357), pp. 385–406. A synopsis of the author's detailed study of the same topic in Ref. 435, Vol. 1, Chaps. 12 and 13. Describes "the process whereby a group of British scientists, science administrators, and government officials came to believe that their country should join CERN" in 1951–52. "During each of the phases through which that process passed, different groups of actors shaped British policy, and their attitudes differed depending on *who* they were and the state of play *when* they entered the scene." (I)

438. **"The Choice of CERN's First Large Bubble Chambers for the Proton Synchrotron (1957–1958),"** John Krige and Dominique Pestre,

Hist. Stud. Phys. Biol. Sci. **16**, 255–79 (1986). Focuses on the debate, involving both scientific and political arguments, that led to the decision to build CERN's first hydrogen bubble chambers. (A)

439. "The CERN Beam-Transport Programme in the Early 1960s," John Krige, in Ref. 49, pp. 218–32. Describes the (original) beam-transport system for the CERN proton synchrotron and examines the beam-transport "crisis" of 1961–62, during which CERN fell behind its principal American rival, Brookhaven National Laboratory, in the race to discover new particles. (I)

440. " 'Monsters' and Colliders in 1961: The First Debate at CERN on Future Accelerators," Dominique Pestre, in Ref. 49, pp. 233–41. Examines the first year (1961) of the spirited debate among European scientists about the generation of CERN accelerators to follow the 600-MeV synchrocyclotron and 28-GeV proton synchrotron. Argues that both an "intellectual" and a "social" historiographical approach is required in order to understand the nature of the debate. (I)

441. Europe's Giant Accelerator: The Story of the CERN 400 GeV Proton Synchrotron, Maurice Goldsmith and Edwin Shaw (Taylor and Francis, London, 1977). A popular description of the design and construction of the Super Proton Synchrotron during the 1970s. (E)

442. CERN—25 Years of Physics, edited by M. Jacob (North-Holland, New York, 1981). A celebration of CERN's 25th anniversary in 1979, with articles on experiments performed at the laboratory. (A)

443. "Highlights of 25 Years of Physics at CERN," L. Van Hove and M. Jacob, in Ref. 442, pp. 16–86. Also in Phys. Reports **62**, 1–86 (1980). Surveys CERN's accelerators and other equipment and then reviews the main areas of experimental and theoretical research at the laboratory since its founding: nuclear and intermediate-energy physics, hadron spectroscopy, hadron collisions at high energy, tests of QCD, and weak interaction physics and high-energy neutrino interactions. (A)

444. "CERN: Past Performances and Future Prospects," Benjamin R. Martin and John Irvine, Research Policy **13**, 183–210, 247–84, and 311–42 (1984). A detailed, comparative study of the management and scientific achievements of the CERN accelerators from 1969 to 1978. (I)

For an account of European particle physics from 1945 to 1953 and the steps that led to the creation of CERN, see also Ref. 200, pp. 326–40.

C. Other laboratories and accelerators

445. Cambridge Physics in the Thirties, edited by John Hendry (Adam Hilger, Bristol, England, 1984). History and scientists' reminiscences of the Cavendish Laboratory in the 1930s. Includes essays on Chadwick's discovery of the neutron and Blackett and Occhialini's demonstration of the existence of the positron. (I)

446. "Origins and Early Days of the Bristol School of Cosmic-Ray Physics," W. O. Lock, Eur. J. Phys. **11**, 193–202 (1990). Traces the career of C. F. Powell, "father of meson physics," and his success in building up the Bristol school during the years 1946–51. (I)

447. "History of the Cyclotron, Part I," M. Stanley Livingston, Phys. Today **12** (10), 18–23 (1959). Reprinted in Ref. 65, pp. 255–60, and in Ref. 78, pp. 261–67. Based on a lecture delivered at the APS spring meeting in 1959. Discusses the author's work with E. O. Lawrence on the first cyclotrons at Berkeley, 1929–34. (E)

448. "History of the Cyclotron, Part II," Edwin M. McMillan, Phys. Today **12** (10), 24–34 (1959). Reprinted in Ref. 65, pp. 261–71, and in Ref. 78, pp. 268–78. Based on a lecture delivered at the APS spring meeting in 1959. Includes reproductions of slides that illustrate the author's survey of the cyclotrons at Berkeley after 1934. (E)

449. "E. O. Lawrence and Particle Accelerators," Chap. 11 of Ref. 121, pp. 223–40. (E)

450. Lawrence and His Laboratory: A History of the Lawrence Berkeley Laboratory, Vol. 1, J. L. Heilbron and Robert W. Seidel (University of California Press, Berkeley, 1989). A detailed history through 1941. (A)

451. Lawrence and His Laboratory: Nuclear Science at Berkeley, 1931–1961, J. L. Heilbron, Robert W. Seidel, and Bruce R. Wheaton (Office for History of Science and Technology, University of California, Berkeley, 1981). A concise, illustrated history of the laboratory's first 30 years. (E)

452. "Early Days in the Lawrence Laboratory (1931–1940)," Edwin M. McMillan, in *New Directions in Physics: The Los Alamos 40th Anniversary Volume,* edited by N. Metropolis, D. M. Kerr, and Gian-Carlo Rota (Academic, New York, 1987), pp. 137–61. A reminiscence, with over two dozen photographs of the laboratory, its equipment, and its inhabitants. (E)

453. "Accelerating Science: The Postwar Transformation of the Lawrence Radiation Laboratory," Robert W. Seidel, Hist. Stud. Phys. Sci. **13**, 375–400 (1983). A sociopolitical history of the expansion of the laboratory and its rise to preeminence in high-energy physics during the years 1944–48. (A)

454. "The First European Cyclotrons," John L. Heilbron, Rivista di Storia della Scienza **3**, 1–44 (1986). A study of the contrast between attitudes toward physics in Europe and the United States during the 1930s. Focuses on the Paris and Copenhagen cyclotrons, which were completed in 1938 with American assistance. (I)

455. "The Story of AdA," Carlo Bernardini, Scientia **113**, 39–44 (1978). On the history of the world's first electron–positron storage ring, AdA (*Anello di Accumulazione*), a prototype built at the Frascati (Italy) Laboratories and operated there and in Orsay, France, during the early 1960s. (A)

456. "Establishing KEK in Japan and Fermilab in the U.S.: Internationalism, Nationalism and High Energy Accelerators," Lillian Hoddeson, Soc. Stud. Sci. **13**, 1–48 (1983). A comparative study of Fermilab and its Japanese competitor KEK during the period 1959–70. Argues that the difference between the institutions' scientific success resulted from national differences in the politics of science funding and the organization of the physics communities. (I)

457. "Fermilab: Founding the First US 'Truly National Laboratory,' " Catherine Westfall, in Ref. 49, pp. 184–217. Sketches U.S. accelerator building during the postwar era and then details the founding of Fermilab from the beginning of planning in 1960 to the attainment of 200-GeV beam energy in early 1972. Focuses on the political and economic pressures that affected the planning and construction of the laboratory. (I)

458. "The Site Contest for Fermilab," Catherine L. Westfall, Phys. Today **42** (1), 44–52 (1989). Discusses the site-selection process and the competition for the 200-GeV accelerator, 1960–67. "By choosing Illinois, the AEC commissioners appeased Midwestern political forces as well as Midwestern particle physicists who had been campaigning for a world-class accelerator in their region for 22 years." (E)

459. Poliscide, Theodore J. Lowi, Benjamin Ginsberg *et al.* (Macmillan, New York, 1976). A "cluster of case studies" focusing on the politics of the erection of Fermilab in the village of Weston, Illinois, in the 1960s. "Each of [the] cases tells part of the same story—from the national perspective, the state perspective, the metropolitan perspective, the county perspective, the perspective of the villagers, and the perspective of the farmers included in the site area." (E)

460. "The First Large-Scale Application of Superconductivity: The Fermilab Energy Doubler, 1972–1983," Lillian Hoddeson, Hist. Stud. Phys. Biol. Sci. **18**, 25–54 (1987). Discusses the planning and completion of Fermilab's "energy doubler" and its large-scale application of superconducting magnets, and compares this case with Brookhaven's less successful superconducting accelerator project. Focuses on institutional and sociological aspects. (A)

461. "The Tevatron," Leon M. Lederman, Sci. Am. **264** (3), 48–55 (1991). Reviews the history of Fermilab's Tevatron program from 1973 to 1991. (E)

462. The Stanford Two-Mile Accelerator, edited by R. B. Neal (Benjamin, New York, 1968). Contains 27 chapters that detail (mostly technical aspects of) the design and construction of the Stanford Linear Accelerator Center and its two-mile linear electron accelerator. Chapters 1–5 ("Introduction," "Aims and Purposes," "History and Development," "Project Administration," and "General Description of SLAC and Two-Mile Accelerator") would be especially useful for historical studies. (I, A)

463. "The Evolution of SLAC and Its Program," Wolfgang Panofsky, Phys. Today 36 (10), 34–41 (1983). A history of the Stanford Linear Accelerator Center and its contributions to particle physics, 1957–83. (E)

464. "The Stanford Linear Collider," John R. Rees, Sci. Am. **261** (4), 58–65 (1989). Discusses the design, construction, and testing of the world's first linear collider, which met the goal of becoming a Z^0 factory in April 1989. (E)

465. "An Anecdotal Account of Accelerators at Cornell," Robert R. Wilson, in Ref. 54, pp. 225–44. (A)

466. History of the ZGS, edited by Joanne S. Day, Alan D. Krisch, and Lazarus G. Ratner (American Institute of Physics, New York, 1980). Proceedings of the Symposium on the History of the Zero Gradient Synchrotron at Argonne National Laboratory. (A)

467. AGS 20th Anniversary Celebration, edited by Neil V. Baggett (Brookhaven National Laboratory, Upton, Long Island, NY, 1980). Proceedings of a symposium held at BNL in May 1980. Contains scientists' brief reminiscences on the early history of the Alternating Gradient Synchrotron and on the major discoveries that were made with the instrument, including the μ-neutrino (M. Schwartz), *CP* violation (V. Fitch), the Ω^- hyperon and Λ_c^+ charmed baryon (N. Samios), and the *J* particle (S. Ting). (Available from the National Technical Information Service, U.S. Dept. of Commerce, 5285 Port Royal Rd., Springfield, VA 22161.) (I)

D. Bubble and spark chambers

468. "Bubble Chambers and the Experimental Workplace," Peter Galison, in *Observation, Experiment, and Hypothesis in Modern Physical Science*, edited by Peter Achinstein and Owen Hannaway (MIT Press, Cambridge, MA, 1985), pp. 309–73. Covers the history of bubble chamber techniques, 1950–66, and the alteration in the criteria of experimental demonstration that the new instruments and work structure shaped. Includes details of D. Glaser's invention of the bubble chamber. (I)

469. "Bubbles, Sparks, and the Postwar Laboratory," Peter Galison, in Ref. 39, pp. 213–51. Discusses the evolution of and competition between bubble chambers and spark chambers in high-energy physics of the 1950s and early 1960s. Views the detectors as belonging to "two competing experimental traditions—the spark chamber tied to a tradition of...'logic' devices, and the bubble chamber linked to the tradition of 'image-producing' instruments." (I)

E. Conferences

470. The Solvay Conferences on Physics: Aspects of the Development of Physics Since 1911, Jagdish Mehra (Reidel, Boston, 1975). Presents synopses of the contributions to each conference from 1911 (the First) to 1973 (the Sixteenth), including the conferences (in 1948, 1961, and 1967) that dealt specifically with particle physics. (A)

471. "A Short History of Shelter Island I," Silvan S. Schweber, in *Shelter Island II* (see Ref. 287), pp. 301–43. Discusses the institutional, political, and scientific aspects of the famous conference of June 1947. (I)

472. "Shelter Island, Pocono, and Oldstone: The Emergence of American Quantum Electrodynamics after World War II," Silvan S. Schweber, Osiris (2nd ser.) 2, 265–302 (1986). An account of institutional, political, and scientific aspects of the Shelter Island Conference of June 1947 and of the subsequent Pocono and Oldstone conferences. Looks principally at the organization and proceedings of the first Shelter Island conference, which marked the beginning of renormalization QED and the beginning of American dominance in theoretical elementary-particle physics. (I)

473. "The Rochester Conferences: The Rise of International Cooperation in High Energy Physics," Robert E. Marshak, Bull. Atom. Sci. **26** (6), 92–98 (1970). Covers the background to the first Rochester conferences on high-energy physics and their effect on the physics community, 1947–60. (E)

474. "Scientific Impact of the First Decade of the Rochester Conferences (1950–1960)," Robert E. Marshak, in Ref. 39, pp. 645–67. Summarizes the scientific highlights of the first ten Rochester conferences. (I)

475. Rochester Roundabout: The Story of High Energy Physics, John Polkinghorne (Longman, Harlow, Essex, England, 1989). A "theorist's eye view" of high-energy physics from 1950 to 1980, provided through reminiscences of the first 20 Rochester conferences. A final chapter assesses developments in light of theories from the philosophy of science. (I)

VIII. BIOGRAPHIES AND AUTOBIOGRAPHIES

Informative, often lengthy biographies and lists of publications of distinguished, deceased scientists, including some particle physicists, are published in the *Obituary Notices* (1932–54) and *Biographical Memoirs* (1955–) of Fellows of the Royal Society and in the *Biographical Memoirs* of the National Academy of Sciences (U.S.). Additional entries for particle physicists (departed and living) can be found in the following inclusive works:

476. McGraw-Hill Modern Scientists and Engineers, 3 vols. (McGraw-Hill, New York, 1980). Previously published as *McGraw-Hill Modern Men of Science.* Provides short biographies of prominent 20th-century scientists and engineers. (E)

477. Pioneers of Science: Nobel Prize Winners in Physics, Robert L. Weber (Heyden, Philadelphia, 1980). Provides short biographies for all 114 physics laureates from 1901 to 1979. (E)

478. The Atomic Scientists: A Biographical History, Henry A. Boorse, Lloyd Motz, and Jefferson Hane Weaver (Wiley, New York, 1989). Reprints much of the historical commentary from Ref. 72. Contains biographical sketches of H. A. Bethe, P. A. M. Dirac, R. P. Feynman, T. D. Lee, J. Schwinger, C. N. Yang, and others. (E)

Books and articles exclusively devoted to the lives of individual scientists include:

479. Alvarez: Adventures of a Physicist, Luis W. Alvarez (Basic Books, New York, 1987). (E)

480. Dirac: A Scientific Biography, Helge Kragh (Cambridge U. P., New York, 1990). (A)

481. Enrico Fermi: Physicist, Emilio Segrè (University of Chicago Press, Chicago, 1970). (I)

482. "Surely You're Joking, Mr. Feynman!": Adventures of a Curious Character, Richard P. Feynman with Ralph Leighton, edited by Edward Hutchings (Norton, New York, 1985); **"What Do *You* Care What Other People Think?": Further Adventures of a Curious Character,** Richard P. Feynman with Ralph Leighton (Norton, New York, 1988); **Tuva or Bust!: Richard Feynman's Last Journey,** Ralph Leighton (Norton, New York, 1991). Entertaining anecdotes from Feynman's life. (E)

483. Interactions: A Journey Through the Mind of a Particle Physicist and the Matter of This World, Sheldon Glashow with Ben Bova (Warner Books, New York, 1988). An autobiography filled with anecdotes and nontechnical discussions of many concepts in particle physics. (E)

484. An American Genius: The Life of Ernest Orlando Lawrence, Herbert Childs (Dutton, New York, 1968). (I)

485. The Autobiography of Robert A. Millikan, Robert A. Millikan (Prentice-Hall, New York, 1950). (I)

486. The Rise of Robert Millikan: Portrait of a Life in American Science, Robert Kargon (Cornell U. P., Ithaca, NY, 1982). (I)

487. Robert Oppenheimer: Letters and Recollections, edited by Alice Kimball Smith and Charles Weiner (Harvard U. P., Cambridge, MA, 1980). A documentary composed of biographical and autobiographical sources covering the period 1922–45, when "Oppie" became an organizer of American theoretical physics and a leading contributor to QED and elementary-particle physics. Interweaves personal letters, Oppenheimer's reminiscences, and recollections by people who knew him. Includes extensive excerpts from T. S. Kuhn's 1963 interview with Oppenheimer for the Archive for History of Quantum Physics. (I)

488. "Fragments of Autobiography," Cecil Frank Powell, in Ref. 101, pp. 7–34. (I)

489. **Rabi: Scientist and Citizen,** John S. Rigden (Basic Books, New York, 1987). (I)
490. **Moments in the Life of a Scientist,** Bruno Rossi (Cambridge U. P., New York, 1990). "Autobiographical notes," including 65 photographs, describing Rossi's career as an experimental physicist and a physics educator. Covers his important work in cosmic-ray physics, his wartime years at Los Alamos, and his later interests in space research. (I)
491. **Rutherford: Simple Genius,** David Wilson (MIT Press, Cambridge, MA, 1983). (A)
492. **"Shôichi Sakata—His Physics and Methodology,"** Shunkichi Hirokawa and Shûzô Ogawa, in Ref. 66, pp. 67–81. Focuses on Sakata's work before and during World War II. (A)
493. **Abdus Salam, A Nobel Laureate from a Muslim Country: A Biographical Sketch,** Abdul Ghani (Ma'aref, Karachi, Pakistan, 1982). (A)
494. **Ideals and Realities: Selected Essays of Abdus Salam,** 3rd ed., edited by C. H. Lai and Azim Kidwai (World Scientific, Singapore, 1989). A selection of essays and talks on the International Centre for Theoretical Physics (Trieste), science in developing countries, Islam, and various aspects of physics. Includes Salam's Nobel lecture of 1979 (Ref. 378) and biographical sketches of Salam by N. Calder, J. Ziman, R. Walgate, and others. Also contains a section with biographical data. (I)
495. **"Fifty Years Up and Down a Strenuous and Scenic Trail,"** Emilio Segrè, Ann. Rev. Nucl. Part. Sci. **31**, 1–18 (1981). An autobiographical account of the author's participation in the development of nuclear and particle physics, 1928–72. (E)
496. **The Joy of Insight: Passions of a Physicist,** Victor Weisskopf (Basic Books, New York, 1991). An autobiography constructed from memory. Includes recollections of the author's work in nuclear and particle physics and his service (from 1961 to 1966) as director general of CERN. (E)
497. **Tabibito** ("The Traveler"), Hideki Yukawa, translated by L. M. Brown and R. Yoshida (World Scientific, Singapore, 1982). An autobiography of Yukawa's early years. (I)

See also Refs. 52, 237, 274, 278, and 446 and the festschrifts and collected works listed in Secs. IV B and IV E.

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Simple demonstration of storing macroscopic particles in a "Paul trap"

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A simple experimental setup can be used to demonstrate the storage of macroscopic dust particles in a "Paul trap." The trap is operated at atmospheric pressure, which results in an efficient "cooling" of the stored particles. Under these conditions, a single anthracene dust particle has been confined for over 2 months. The device is well suited to show the formation of ordered structures when a number of "cooled" species are trapped. Due to its overall simplicity, the setup can be used in lectures, student laboratories, etc.

I. INTRODUCTION

Different concepts of trapping atomic particles nowadays allow one to perform experiments in which individual species are quasipermanently kept at rest in free space. These developments make feasible a number of conceptually new experiments with accuracies of data that are orders of magnitude smaller than those obtained with conventional spectroscopic methods. A representative example is the outstanding work by H. G. Dehmelt and his coworkers (University of Washington, Seattle) with respect to trapping single electrons. The resulting structure of electronic terms of such an electron confined in a "Penning trap" (static magnetic field and static electric quadrupole field) is ideally suited for high-precision measurements of the electron g factor. These experiments currently provide the most stringent tests on the concepts of quantum electrodynamics. In a recent paper appearing in this Journal, Dehmelt briefly reviews features and perspectives of spectroscopy with trapped particles.[1]

The purpose of this paper is to describe a simple setup to demonstrate features of a "Paul trap," i.e., trapping of charged particles in ac–electric quadrupole fields. This trap was developed by W. Paul (Universität Bonn)[2] and has proven to be a powerful method in storage and spectroscopy of ions. Fascinating new types of experiments with this type of trap have been performed in recent years: storage and detection of a single ion,[3] laser sideband "cooling" of the motion,[4] and formation of ordered structures[5,6] of trapped atomic ions, studies with respect to "quantum jumps,"[7,8] microwave[9] and laser spectroscopy[10] with resonances of very high-quality factors. Direct applications of those experiments are expected to provide improved frequency/time standards.[11]

