

Resource Letter SM-1: The Standard Model and Beyond

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This Resource Letter provides a guide to literature on the Standard Model of elementary particles and possible extensions. In the successful theory of quarks and leptons and their interactions, important questions remain, such as the mechanism of electroweak symmetry breaking, the origin of quark and lepton masses, the source of the baryon asymmetry of the Universe, and the makeup of its matter and energy density. References are cited for quarks and leptons, gauge theories, color and chromodynamics, weak interactions, electroweak unification, CP violation, dynamics of heavy quarks, Higgs bosons, precision electroweak measurements, supersymmetry, dynamical electroweak symmetry breaking, composite quarks and leptons, grand unification and extended gauge groups, string theories, large extra dimensions, neutrino masses, cosmic microwave background radiation, dark matter, dark energy, accelerator facilities, and non-accelerator experiments.

I. INTRODUCTION

The “Standard Model” of elementary particle physics encompasses the progress of the past half-century in understanding the weak, electromagnetic, and strong interactions. During this period tremendous strides were made in bringing quantum field theory to bear upon a wide variety of phenomena.

The arsenal of techniques for understanding the strong interactions in the 1960s included principles based on analyticity, unitarity, and symmetry. The successes of the emerging quark model often seemed mysterious. The ensuing decade yielded a theory of strong interactions, quantum chromodynamics (QCD), permitting calculations of a wide range of properties of the *hadrons*, or strongly interacting particles, and has been validated by the discovery of its force-carrier, the *gluon*.

In the 1960s the weak interactions were represented by a phenomenological four-fermion theory of no use for higher-order calculations. Attempts to describe weak interactions with heavy boson exchange bore fruit when these interactions were unified with electromagnetism and a suitable mechanism for generation of heavy boson mass was found. This *electroweak theory* has been spectacularly successful, leading to the prediction and observation of the W and Z bosons and to precision tests confirming the theory’s validity in higher-order calculations.

This Resource Letter begins with sections devoted to the resources available for study of the Standard Model of particle physics and its extensions: periodicals (II),

conference proceedings (III), texts and reviews (IV), historical references (V), popular literature (VI), Internet resources (VII), and a guide to Nobel prizes related to the subject (VIII).

A description of Standard Model research literature follows. In Section IX, based in part on [1], the ingredients of the standard model — the quarks and leptons and their interactions — are introduced, and QCD is discussed briefly. The unified theory of weak and electromagnetic interactions is described, its role in explaining CP violation is explained, and its missing piece — the Higgs boson — is mentioned.

Important questions remain that are not addressed in the Standard Model. These include the unification of the electroweak and strong interactions (possibly including gravity), the origin of quark and lepton masses, the source of the baryon asymmetry of the Universe, and the nature of its unseen matter and energy density. Some proposed Standard Model extensions devoted to these problems are noted in Section X. Concrete evidence for physics beyond the Standard Model, including neutrino masses, cosmic microwave background radiation, dark matter, and “dark energy,” is described in Section XI. A variety of experimental methods are appropriate for probing these phenomena (Section XII). A brief summary (Section XIII) concludes.

1. “The Standard Model in 2001,” J. L. Rosner, based on five lectures at the 55th Scottish Universities’ Summer School in Particle Physics, St. Andrews, Scotland, August 7–23, 2001. Published in **Heavy Flavour Physics (Theory and Experimental Results on Heavy Quark Physics and CP Violation)**, edited by C. T. H. Davies and S. M. Playfer (Institute of Physics, Bristol and Philadelphia, 2002), pp. 1–56. (I)

II. PERIODICALS

The literature on the Standard Model of particle physics and its extensions is extensive and international, but a good sense of the field can be gained by perusing about a dozen main journals. Subsequent sections are devoted to other means of gaining information about this rapidly changing subject.

Instrumentation journals with some articles on elementary particle physics:

IEEE Transactions on Nuclear Science
Nuclear Instruments and Methods A
Review of Scientific Instruments

Journals devoted primarily or largely to elementary particle physics:

European Journal of Physics C
Fizika Elementarnykh Chastits i Atomnogo Yadra (Soviet Journal of Particles and Nuclei)
International Journal of Modern Physics A
Journal of High Energy Physics (“JHEP”; electronic)
Journal of Physics G
Modern Physics Letters A
Nuclear Physics B

Nuovo Cimento A
Physical Review D
Physics Letters B
Progress of Theoretical Physics (Kyoto)
Yadernaya Fizika (Soviet Journal of Nuclear Physics –1992; Physics of Atomic Nuclei 1993–).
Zeitschrift für Physik C, now absorbed into *European Journal of Physics C*
Zhurnal Eksperimental'nyi i Teoreticheskii Fizika (Soviet Physics - JETP)

Laboratory newsletters:

CERN Courier (European Center for Nuclear Research); web address:
<http://www.cerncourier.com/>
FermiNews (Fermilab, USA); web address:
<http://www.fnal.gov/pub/ferminews/>
SLAC Beam Line (Stanford Linear Accelerator Center); web address:
<http://www.slac.stanford.edu/pubs/beamline/>

Rapid publication journals with section devoted to particle physics:

Chinese Physics Letters
Europhysics Letters
Physical Review Letters
Pis'ma v Zhurnal Eksperimental'nyi i Teoreticheskii Fizika (JETP Letters)

Review journals:

Annals of Physics (N.Y.)
Annual Review of Nuclear and Particle Science
Physics Reports
Reports on Progress in Physics
Reviews of Modern Physics

Other journals with frequent articles on particle physics or related subjects:

Acta Physica Polonica
American Journal of Physics
Astroparticle Physics
Astrophysical Journal
Nature
New Scientist
Physics Today (AIP)
Physics World (IOP)
Progress of Theoretical Physics (Japan)
Science
Science News
Scientific American

III. CONFERENCE PROCEEDINGS

The latest biennial “Rochester” Conference in High Energy Physics was held in Amsterdam in July 2002; the previous one was in Osaka in 2000 [2]. In odd-numbered

years there occur both the International Symposium on Lepton and Photon Interactions at High Energies, of which the most recent was in Rome [3], and the International Europhysics Conference on High Energy Physics, most recently held in Budapest [4]. The locations of each of these conferences since 1990 are summarized in Table 1. A search of the SPIRES listing at the SLAC Library (see Sec. VII) is the easiest way to find the corresponding Proceedings.

Table 1: Locales of major high energy physics conferences since 1990. (1) International Conference on High Energy Physics (“Rochester” Conference); (2) International Symposium on Lepton and Photon Interactions at High Energies; (3) International Europhysics Conference on High Energy Physics.

(1)		(2)		(3)	
Year	Location	Year	Location	Year	Location
1990	Singapore	1991	Geneva	1991	Geneva
1992	Dallas, TX	1993	Ithaca, NY	1993	Marseille
1994	Glasgow	1995	Beijing	1995	Brussels
1996	Warsaw	1997	Hamburg	1997	Jerusalem
1998	Vancouver	1999	Stanford	1999	Tampere, Finl.
2000	Osaka	2001	Rome	2001	Budapest
2002	Amsterdam	2003	Fermilab	2003	Aachen

2. **XXX International Conference on High Energy Physics (ICHEP 2000)**, Osaka, Japan, 27 Jul - 2 Aug 2000, edited by C. S. Lim and T. Yamanaoka (World Scientific, Singapore, 2001). (I)
3. **20th International Symposium on Lepton and Photon Interactions at High Energies (Lepton Photon 01)**, Rome, Italy, 23–28 July 2001, edited by J. Lee-Franzini, P. Franzini, and F. Bossi (World Scientific, Singapore, 2002). (I)
4. **International Europhysics Conference on High Energy Physics (High Energy Physics 2001: Proceedings)**, Budapest, Hungary, July 2001 edited by D. Horvath, P. Levai, and A. Patkos (JHEP, 2001). (I)

IV. TEXTBOOKS, EXPOSITIONS, AND REVIEW ARTICLES

This section indicates textbooks and articles at the intermediate or advanced level. For popularizations at the non-specialist’s level, see Section VI.

A. Textbooks

1. *Quantum field theory:*

5. **Quantum Field Theory**, C. Itzykson and J. B. Zuber (McGraw-Hill, New York, 1980). (A)
6. **Gauge Theory of Elementary Particle Physics**, T. P. Cheng and L. F. Li (Clarendon, Oxford, 1984). (A)
7. **Field Theory: A Modern Primer**, 2nd Edition, P. Ramond, *Frontiers of Physics* **74**, 1–329 (1989). (A)
8. **Quantum Field Theory**, L. S. Brown (Cambridge Univ. Press, 1992). (A)
9. **Quantum Field Theory**, F. Mandl and G. Shaw, Revised Edition (Wiley-Interscience, Chichester, UK, 1993). (I)
10. **An Introduction to Quantum Field Theory**, M. E. Peskin and D. V. Schroeder (Addison-Wesley, Reading, MA, 1995). (A)
11. **The Quantum Theory of Fields. Vol. 1: Foundations**, S. Weinberg (Cambridge Univ. Press, 1995). (A)
12. **The Quantum Theory of Fields. Vol. 2: Modern Applications**, S. Weinberg (Cambridge Univ. Press, 1996). (A)
13. **Quantum Field Theory**, 2nd Edition, L. H. Ryder (Cambridge Univ. Press, 1996). (I)

2. Standard model (electroweak and strong interactions):

14. **Leptons and Quarks**, L. B. Okun' (North-Holland, Amsterdam, 1982). (I)
15. **Quarks and Leptons: An Introductory Course in Modern Particle Physics**, F. Halzen and A. D. Martin (Wiley, New York, 1984). (I)
16. **Weak Interactions and Modern Particle Theory**, H. Georgi (Benjamin/Cummings, Menlo Park, CA, 1985). (I)
17. **Dynamics of the Standard Model**, J. F. Donoghue, E. Golowich, and B. R. Holstein, *Cambridge Monogr. Part. Phys. Nucl. Phys. Cosmol.* **2**, 1–540 (1992). (I)
18. **Gauge Theories of the Strong, Weak, and Electromagnetic Interactions**, C. Quigg, (Addison-Wesley, 1997). (I)
19. **An Introduction to the Standard Model of Particle Physics**, W. N. Cottingham and D. A. Greenwood (Cambridge Univ. Press, 1998). (I)

3. CP violation:

20. **CP Violation**, edited by C. Jarlskog (World Scientific, Singapore, 1989). (I)

21. **CP Violation**, I. I. Y. Bigi and A. I. Sanda, Cambridge Monogr. Part. Phys. Nucl. Phys. Cosmol. **9**, 1–382 (2000). (I)
22. **CP Violation**, G. C. Branco, L. Lavoura, and J. P. Silva (Clarendon Press, Oxford, 1999). (I)

4. *Elementary particle phenomenology:*

23. **An Introduction to Quarks and Partons**, F. E. Close (Academic Press, London, 1979). (I)
24. **Concepts of Particle Physics**, K. Gottfried and V. F. Weisskopf (Oxford Univ. Press, 1984 [Vol. 1]; 1986 [Vol. 2]). (I)
25. **The Experimental Foundations of Particle Physics**, R. N. Cahn and G. Goldhaber (Cambridge Univ. Press, 1989). (I)
26. **Collider Physics**, V. D. Barger and R. J. N. Phillips, updated edition (Addison-Wesley, Redwood City, CA, 1997). (I)
27. **Introduction to High-Energy Physics**, 4th Edition, D. H. Perkins (Cambridge Univ. Press, 2000). (I)

5. *Symmetries:*

28. **The Eightfold Way**, M. Gell-Mann and Y. Ne'eman (New York, Benjamin, 1964). (I)
29. **Lie Groups, Lie Algebras, and Some of Their Applications**, R. Gilmore (Wiley-Interscience, New York, 1974). (I)
30. **Semi-Simple Lie Algebras and Their Representations**, R. N. Cahn (Benjamin/Cummings, 1984). (I) See also:
<http://phyweb.lbl.gov/~rncahn/www/liealgebras/book.html>.
31. **Lie Algebras in Particle Physics**, 2nd Edition, H. Georgi (Perseus Books, 1999). (I)

6. *Higgs boson(s):*

32. **The Higgs Hunter's Guide**, J. F. Gunion, H. E. Haber, G. Kane, and S. Dawson (Addison-Wesley, Redwood City, CA, 1990). (I)
33. **Perspectives on Higgs Physics**, edited by G. L. Kane (World Scientific, Singapore, 1993). (I)
34. **Perspectives on Higgs Physics II**, edited by G. L. Kane (World Scientific, Singapore, 1997). (I)

7. *Neutrinos:*

35. **Solar Neutrinos: The First Thirty Years**, edited by J. N. Bahcall *et al.* (Frontiers in Physics, 2002). (I)

8. *Supersymmetry:*

36. **Supersymmetry and Supergravity**, 2nd Edition, J. Wess and J. Bagger (Princeton Univ. Press, Princeton, NJ, 1992). (A)
37. **Perspectives on Supersymmetry**, edited by G. L. Kane (World Scientific, Singapore, 1998). (I)
38. **The Quantum Theory of Fields. Vol. 3: Supersymmetry**, S. Weinberg (Cambridge Univ. Press, 2000). (A)

9. *Beyond the Standard Model:*

39. **Electroweak Symmetry Breaking and New Physics at the TeV Scale**, edited by T. Barklow *et al.* (World Scientific, Singapore, 1996). (A)
40. **Journeys beyond the Standard Model**, P. Ramond (Perseus Books, Reading, Mass., 1999). (I)

10. *String theory:*

41. **Superstring Theory. Vol. 1: Introduction**, M. B. Green, J. H. Schwarz, and E. Witten (Cambridge Univ. Press, 1987). (A)
42. **Superstring Theory. Vol. 2: Loop Amplitudes, Anomalies, and Phenomenology**, M. B. Green, J. H. Schwarz, and E. Witten (Cambridge Univ. Press, 1987). (A)
43. **String Theory. Vol. 1: An Introduction to the Bosonic String**, J. Polchinski (Cambridge Univ. Press, 1998). (A)
44. **String Theory. Vol. 2: Superstring Theory and Beyond**, J. Polchinski (Cambridge Univ. Press, 1998). (A)

B. Expositions (summer school lectures, collections of articles)

A conference on kaon physics was held at the University of Chicago in 1999 as part of a series. A volume of articles based on the conference gives an overview of the field [45].

Regular summer schools in particle physics are organized in several locales, including Boulder (Colorado), Cargèse (Corsica), CERN, Erice (Sicily), and SLAC

(Stanford). The topics typically vary from year to year but there are frequently lectures on various aspects of the Standard Model (see, e.g., the lectures on CP violation by Nir [46] and the overview by Rosner [1]).

The Theoretical Advanced Study Institute (TASI) at the University of Colorado was devoted in June of 2000 to flavor physics, a major aspect of the Standard Model, and the proceedings also contain various aspects of proposed physics beyond the Standard Model [47]. For specific reviews given at summer schools, see the subsection on Reviews, below.

45. **Kaon Physics**, edited by J. L. Rosner and B. Winstein (University of Chicago Press, 2001). (I)
46. “CP violation in and Beyond the Standard Model,” Y. Nir, Lectures given at 27th SLAC Summer Institute on Particle Physics: CP Violation in and Beyond the Standard Model (SSI 99), Stanford, California, 7–16 July 1999, Institute for Advanced Study report IASSNS-HEP-99-96, hep-ph/9911321. (A)
47. **TASI-2000: Flavor Physics for the Millennium**, edited by J. L. Rosner (World Scientific, Singapore, 2001). (I)

C. Review Articles

A number of review articles will be referred to in the narrative of the Standard Model and its extensions (Secs. X–XIII). These include the following:

1. *Gauge theories:*

48. “Gauge Theories,” E. S. Abers and B. W. Lee, Phys. Rep. **9**, 1–141 (1973). (I)

2. *Standard Model:* In addition to Rosner (2001) [1], see:

49. “The Electroweak Theory,” C. Quigg, in [47], pp. 3–67.

3. *Hadron spectra and quarks:*

50. “Charm and Beyond,” T. Appelquist, R. M. Barnett, and K. D. Lane, Ann. Rev. Nucl. Part. Sci. **28**, 387 (1978). (I)
51. “Charmonium and Gluons: Basic Experimental Facts and Theoretical Introduction,” V. A. Novikov *et al.*, Phys. Rep. **41**, 1–133 (1978). (I)
52. “Hadron Spectra and Quarks,” S. Gasiorowicz and J. L. Rosner, Am. J. Phys. **49**, 954–984 (1981). (I)
53. “Heavy Quark Systems,” W. Kwong, C. Quigg, and J. L. Rosner, Ann. Rev. Nucl. Part. Sci. **37**, 325–382 (1987). (I)
54. “Upsilon Spectroscopy,” W. Buchmüller and S. Cooper, Adv. Ser. Direct. High Energy Phys. **1**, 412–487 (1988). (I)

55. “Heavy Quark Symmetry,” N. Isgur and M. B. Wise, *Adv. Ser. Direct. High Energy Phys.* **10**, 549–572 (1992). (I)

4. *Group theory:*

56. “Group Theory for Unified Model Building,” R. Slansky, *Phys. Rep.* **79**, 1–128 (1981). (I)

5. *Neutrino physics:*

Massive neutrinos and neutrino oscillations:

57. “Massive Neutrinos and Neutrino Oscillations,” S. M. Bilenky and S. T. Petcov, *Rev. Mod. Phys.* **59**, 671–754 (1987). (I)
58. “Neutrino Mass, Mixing, and Oscillation,” B. Kayser, in [47], pp. 625–650; “Neutrino Mass, Mixing, and Flavor Change,” B. Kayser, hep-ph/0211134, to appear in **Neutrino Mass**, edited by G. Altarelli and K. Winter (Springer Tracts in Modern Physics, 2002). (I)
59. “Oscillations of Atmospheric Neutrinos,” C. K. Jung, T. Kajita, T. Mann, and C. McGrew, *Ann. Rev. Nucl. Part. Sci.* **51**, 451–488 (2001). (I)
60. See the web page of John N. Bahcall: <http://www.sns.ias.edu/~jnb/> for a list of review articles as well as up-to-the-minute information on neutrino oscillation parameters.

Precision electroweak measurements using neutrinos:

61. “Precision Measurements with High Energy Neutrino Beams,” J. M. Conrad, M. H. Shaevitz, and T. Bolton, *Rev. Mod. Phys.* **70**, 1341–1392 (1998). (I)

6. *Supersymmetry:*

62. “A Supersymmetry Primer,” S. P. Martin, in **Perspectives on Supersymmetry II**, edited by G. L. Kane (World Scientific, Singapore, 1997), pp. 1–98. (I) A current version may be found at <http://zippy.physics.niu.edu/primer.shtml> .
63. “Report of the Beyond the MSSM Subgroup for the Tevatron Run II SUSY / Higgs Workshop,” to be published in the proceedings of Physics at Run II: Workshop on Supersymmetry / Higgs (Summary Meeting, Batavia, IL, 19–21 Nov. 1998), preprint hep-ph/0006162 (unpublished). (A)
64. “Report of the SUGRA Working Group for Run II of the Tevatron,” S. Abel *et al.*, to be published in the proceedings of Physics at Run II: Workshop on Supersymmetry / Higgs (Summary Meeting, Batavia, IL, 19–21 Nov. 1998), preprint hep-ph/0003154 (unpublished). (A)

65. “Low-Scale and Gauge-Mediated Supersymmetry Breaking at the Fermilab Tevatron Run II,” R. Culbertson *et al.*, Fermilab report FERMILAB-PUB-00-251-T, hep-ph/0008070 (unpublished). (A)
66. “The Snowmass Points and Slopes: Benchmarks for SUSY Searches,” B. C. Allanach *et al.*, presented at APS/DPF/DPB Summer Study on the Future of Particle Physics (Snowmass 2001), Snowmass, Colorado, 30 June - 21 July 2001, Eur. Phys. J. C **25**, 113-123 (2002). (A)
67. “TASI Lectures: Weak Scale Supersymmetry – a Top-Motivated Bottom-Up Approach,” G. L. Kane, preprint hep-ph/0202185 (unpublished). (I)
68. “Supersymmetry, Supergravity, and Particle Physics,” H. P. Nilles, Phys. Rep. **110**, 1–162 (1984). (I)
69. “The Search for Supersymmetry: Probing Physics Beyond the Standard Model,” H. E. Haber and G. L. Kane, Phys. Rep. **117**, 75–263 (1985). (I)
70. “Introducing Supersymmetry,” M. F. Sohnius, Phys. Rep. **128**, 39–204 (1986). (I)

7. *Extended gauge theories:*

71. “Low-Energy Phenomenology of Superstring Inspired E_6 Models,” J. L. Hewett and T. G. Rizzo, Phys. Rep. **183**, 193–381 (1989). (A)

8. *Atomic parity violation:*

72. “A Bibliography of Atomic Parity Violation and Electric Dipole Moment Experiments,” C. E. Wieman, in [47], pp. 373–375. (I)

9. *Particle properties and general lore:*

A wide variety of mini-reviews of various aspects of the Standard Model may be found in the Review of Particle Physics published by the Particle Data Group:

73. “Review of Particle Physics,” K. Hagiwara *et al.* (Particle Data Group), Phys. Rev. D **66**, 010001 (2002). (I)

D. Other Resource Letters

74. “Resource Letter WI-1: Weak Interactions,” B. R. Holstein, Am. J. Phys. **45**, 1033–1039 (1977). (E–A)
75. “Resource Letter NP-1: New Particles,” Jonathan L. Rosner, Am. J. Phys. **48**, 90–103 (1980). (Particles with charmed and beauty quarks.) (E–A)
76. “Resource Letter SP-2: Symmetry and Group Theory in Physics,” J. Rosen, Am. J. Phys. **49**, 304–319 (1981). (E–A)

77. “Resource Letter Q-1: Quarks,” O. W. Greenberg, *Am. J. Phys.* **50**, 1074–1089 (1982). (E–A)
78. “Resource Letter CPP-1: Cosmology and Particle Physics,” D. Lindley, E. W. Kolb, and D. N. Schramm, *Am. J. Phys.* **56**, 492–501 (1988). (E–A)
79. “Resource Letter GI-1: Gauge Invariance,” T. P. Cheng and L. F. Li, *Am. J. Phys.* **56**, 586–600 (1988). (E–A)
80. “Resource Letter HEPP-1: History of Elementary Particle Physics,” R. C. Hovis and H. Kragh, *Am. J. Phys.* **59**, 779–807 (1991). (E–A)
81. “Quantum Chromodynamics,” A. S. Kronfeld and C. Quigg, in preparation. (E–A)

V. HISTORICAL REFERENCES

A symposium on the history of Symmetries in Physics from 1600 to 1980 [82] contains many informative articles. For a series of conferences on the history of particle physics, culminating in the rise of the Standard Model, see [83, 84, 85]. The history of quantum electrodynamics is detailed in [86], while Pais [87] has chronicled the development of particle physics with particular emphasis on its earlier aspects. A review of some later developments is given in [88]. Personal memoirs include those of a theorist with close ties to experiment (Sam B. Treiman [89]) and a Nobel-prize-winning experimentalist (Jack Steinberger [90]). A collection of articles on supersymmetry with a historical flavor is based on a recent symposium [91]. Two excellent accounts of experimental high energy physics by P. Galison are [92] and [93].

82. **First International Meeting on the History of Scientific Ideas**, St. Feliu de Guixols, Catalonia, Spain, Sept. 20–26, 1983, edited by M. G. Doncel, A. Hermann, L. Michel, and A. Pais (Barcelona, Autonomia Univ., Phys. Dept. 1987). (I)
83. **The Birth of Particle Physics. Proceedings, International Symposium, Batavia, USA, May 28–31, 1980**, edited by L. M. Brown and L. Hoddeson (Cambridge Univ. Press, 1983). (I)
84. **Pions to Quarks: Particle Physics in the 1950s. Proceedings, 2nd International Symposium on the History of Particle Physics, Batavia, USA, May 1–4, 1985**, edited by L. M. Brown, L. Hoddeson, and M. Dresden (Cambridge Univ. Press, 1989). (I)
85. **The Rise of the Standard Model: Particle Physics in the 1960s and 1970s**, edited by L. Hoddeson, L. Brown, M. Riordan, and M. Dresden, based on 3rd International Symposium on the History of Particle Physics: The Rise of the Standard Model, Stanford, CA, 24–27 June 1992 (Cambridge Univ. Press, 1997). (I)

86. **QED and the Men Who Made It: Dyson, Feynman, Schwinger, and Tomonaga**, S. S. Schweber (Princeton University Press, 1994). (I)
87. **Inward Bound**, A. Pais (Clarendon Press, Oxford, 1986). (I)
88. “Elementary Particle Physics in the Second Half of the 20th Century,” V. L. Fitch and J. L. Rosner, in **Twentieth Century Physics**, edited by L. M. Brown, A. Pais, and B. Pippard, Vol. 2, pp. 635–794 (IOP, Philadelphia, 1994). (I)
89. “A Life in Particle Physics,” S. Treiman, *Ann. Rev. Nucl. Part. Sci.* **46**, 1–30 (1996). (E)
90. “Early Particles,” J. Steinberger, *Ann. Rev. Nucl. Part. Sci.* **47**, xiii–xlii (1997). (E)
91. **The Supersymmetric World: The Beginning of the Theory**, edited by G. L. Kane and M. Shifman (World Scientific, Singapore, 2000). (A)
92. **How Experiments End**, P. Galison (Univ. of Chicago Press, 1987). (I)
93. **Image and Logic: A Material Culture of Microphysics**, P. Galison (Univ. of Chicago Press, 1997). (I)

VI. POPULAR LITERATURE

A. Books

For descriptions of particle theory in a cosmological context see [94, 95]. A well-written account of the experiments that led to the idea of quarks being taken seriously is given in [96]. The goals of particle theory are described in [97, 98, 99], while [100, 101] give the case for a fully unified theory. The ongoing search for the Higgs particle and many other efforts in particle physics are treated by [102]. Gordon Fraser, the former editor of the *CERN Courier*, has written or edited several fine books on particle physics aimed at general audiences [103, 104, 105, 106]. One recent popular book on quantum mechanics has been written by Sam Treiman [107]. Many fine popularizations have been written by Richard P. Feynman, including his book on quantum electrodynamics [108] and his Dirac Memorial Lecture, jointly in a volume with that by Steven Weinberg [109].

94. **The First Three Minutes: a Modern View of the Origin of the Universe**, S. Weinberg (Basic Books, New York, 1977). (I)
95. **The Cosmic Code: Quantum Physics as the Language of Nature**, H. R. Pagels (Simon and Schuster, New York, 1982). (E)
96. **The Hunting of the Quark: A True Story of Modern Physics**, Michael Riordan (Simon and Schuster, New York, 1987). (E)

97. **Longing for the Harmonies: Themes and Variations from Modern Physics**, F. Wilczek and B. Devine (Norton, New York, 1988). (E)
98. **The Particle Garden**, G. Kane (Addison-Wesley, Helix Books, New York, 1995). (E)
99. **In Search of the Ultimate Building Blocks**, G. 't Hooft (Cambridge Univ. Press, 1997). (E)
100. **The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest of the Ultimate Theory**, B. R. Greene (Norton, New York, 1999). (E)
101. **Dreams of a Final Theory: The Search for the Fundamental Laws of Nature**, S. Weinberg (Pantheon Books, New York, 1992). (E)
102. **The God Particle: If the Universe is the Answer, What is the Question?**, L. M. Lederman and D. Teresi (Houghton Mifflin, Boston, MA, 1993). (E)
103. **The Search for Infinity: Solving the Mysteries of the Universe**, G. Fraser, E. Lillestøl, and I. Sellevåg (Facts on File, New York, 1995). (E)
104. **The Quark Machines: How Europe Fought the Particle Physics War**, G. Fraser (Institute of Physics, Bristol and Philadelphia, 1997). (E)
105. **The Particle Century**, edited by G. Fraser (Institute of Physics, Bristol and Philadelphia, 1998). (E)
106. **Antimatter: The Ultimate Mirror**, G. Fraser (Cambridge Univ. Press, 2000). (E)
107. **The Odd Quantum**, S. Treiman (Princeton Univ. Press, 1999). (E)
108. **QED: The Strange Theory of Light and Matter**, R. P. Feynman (Princeton Univ. Press, 1985). (E)
109. **Elementary Particles and the Laws of Physics: The 1986 P. A. M. Dirac Memorial Lectures**, R. P. Feynman and S. Weinberg (Cambridge Univ. Press, 1987). (I)

B. Articles

Instructive popular articles (in more or less chronological order) include ones by Lederman on the discovery of the Upsilon particle (the first evidence for the b quark) [110], 't Hooft on gauge theories [111], Wilczek [112] and Quinn and Witherell [113] on matter-antimatter asymmetry, Georgi on quark-lepton and strong-electroweak unification [114], Weinberg [115], Losecco *et al.* [116], and Langacker [117] on proton

decay, Quigg on elementary particles and forces [118], Haber and Kane on supersymmetry [119], Veltman on the Higgs boson [120], Krauss on dark matter in the Universe [121], Green [122] and Duff [123] on string theory, Rees on the Stanford Linear Collider [124], Bahcall on the solar neutrino problem [125], Myers and Picasso on the LEP Collider at CERN [126], Lederman on the Fermilab Tevatron [127], Feldman and Steinberger on measurements at LEP and SLC suggesting the existence of three families of quarks and leptons [128], Liss and Tipton on the discovery of the top quark [129], Hogan *et al.* on supernova surveys and the accelerating Universe [130], Kearns *et al.* on detecting massive neutrinos [131], Weinberg on the goal of a truly unified theory [132] (see below for an Internet link on this article), Llewellyn Smith on the Large Hadron Collider [133], Caldwell and Kamionkowski [134] and Gibbs [135] on the cosmic microwave background radiation, Ostriker and Steinhardt on “dark energy” [136], and Arkani-Hamed *et al.* [137, 138] on large extra dimensions. *The Economist* carries frequent and well-informed articles on progress in high energy physics (see, e.g., [139]). Shorter news articles appear regularly in *Nature*, *Science*, and *Scientific American*.

110. “The Upsilon Particle,” L. M. Lederman, *Sci. Am.* **239** (4), 72–80 (1978). (E)
111. “Gauge Theories of the Forces Between Elementary Particles,” G. ’t Hooft, *Sci. Am.* **242** (6), 104–138 (1980). (E)
112. “The Cosmic Asymmetry Between Matter and Antimatter,” F. Wilczek, *Sci. Am.* **243** (6), 82–90 (1980). (E)
113. “The Asymmetry Between Matter and Antimatter,” H. R. Quinn and M. S. Witherell, *Sci. Am.* **279** (4), 76–81 (1998). (E)
114. “A Unified Theory of Elementary Particles and Forces,” H. Georgi, *Sci. Am.* **244** (4), 48–63 (1981). (E)
115. “The Decay of the Proton,” S. Weinberg, *Sci. Am.* **244** (6), 64–75 (1981). (E)
116. “The Search for Proton Decay,” J. M. Losecco, F. Reines, and D. Sinclair, *Sci. Am.* **252** (6), 54–62 (1985).
117. “Proton Decay,” P. Langacker, in **Proceedings: In celebration of the discovery of the neutrino** (Benjamin Franklin Symposium, 29 Apr - 1 May 1992, Philadelphia, Pennsylvania), edited by C. E. Lane and R. I. Steinberg (World Scientific, River Edge, NJ, 1993), pp. 129–150. (I)
118. “Elementary Particles and Forces,” C. Quigg, *Sci. Am.* **252** (4) 84–95 (1985). (E)
119. “Is Nature Supersymmetric?,” H. E. Haber and G. L. Kane, *Sci. Am.* **254** (6), 52–60 (1986). (E)
120. “The Higgs Boson,” M. J. G. Veltman, *Sci. Am.* **255** (5), 76–84 (1986). (E)

121. “Dark Matter in the Universe,” L. M. Krauss, *Sci. Am.* **255** (6), 58–68 (1986). (E)
122. “Superstrings,” M. B. Green, *Sci. Am.* **255** (3), 48–60 (1986). (E)
123. “The Theory Formerly Known as Strings,” M. J. Duff, *Sci. Am.* **278** (2) 64–69 (1998). (E)
124. “The Stanford Linear Collider,” J. R. Rees, *Sci. Am.* **261** (4), 58–65 (1989). (E)
125. “The Solar Neutrino Problem,” J. N. Bahcall, *Sci. Am.* **262** (5), 54–61 (1990). (E)
126. “The LEP Collider,” S. Myers and E. Picasso, *Sci. Am.* **263** (1), 54–61 (1990). (E)
127. “The Tevatron,” L. M. Lederman, *Sci. Am.* **264** (3), 48–55 (1991). (E)
128. “The Number of Families of Matter,” G. Feldman and J. Steinberger, *Sci. Am.* **264** (2), 70–75 (1991). (E)
129. “The Discovery of the Top Quark,” T. M. Liss and P. L. Tipton, *Sci. Am.* **277** (3), 54–59 (1997). (E)
130. “Surveying Space-Time with Supernovae,” C. J. Hogan , R. P. Kirshner, and N. B. Suntzeff, *Sci. Am.* **280** (1) 28–33 (1999). (E)
131. “Detecting Massive Neutrinos,” E. Kearns, T. Kajita, and Y. Totsuka, *Sci. Am.* **281** (2), 64–71 (1999). (E)
132. “A Unified Physics by 2050?,” S. Weinberg, *Sci. Am.* **281** (6), 68–75 (1999). (E)
133. “The Large Hadron Collider,” C. H. Llewellyn Smith, *Sci. Am.* **283** (1), 70–77 (2000). (E)
134. “Echoes from the Big Bang,” R. R. Caldwell and M. Kamionkowski, *Sci. Am.* **284** (1), 38–43 (2001). (E)
135. “Ripples in Space-Time,” W. W. Gibbs, *Sci. Am.* **286** (4), 62–71 (2002). (E)
136. “The Quintessential Universe,” J. P. Ostriker and P. J. Steinhardt, *Sci. Am.* **284** (1) 46–53 (2001). (E)
137. “The Universe’s Unseen Dimensions,” N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, *Sci. Am.* **283** (2) 62–69 (2000). (E)
138. “Large Extra Dimensions: A New Arena for Particle Physics,” N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, *Physics Today* **55** (2), 35–40 (2002). (I)

139. The Economist **362** (8254), January 5, 2002: “With All Thy Getting, Get Understanding,” p. 12; “A Survey of the Universe,” pp. 47–58.

VII. INTERNET RESOURCES

A. Preprints

A comprehensive repository of preprints on experimental and theoretical particle physics may be found at <http://arXiv.org/>, including experimental papers at <http://arXiv.org/archive/hep-ex>, phenomenological papers (theory papers dealing with experiment) at <http://arXiv.org/archive/hep-ph>, and more abstract theoretical papers at <http://arXiv.org/archive/hep-th>. The SPIRES system at Stanford Linear Accelerator Center: <http://www.slac.stanford.edu/spires/> lists a number of different categories, including books, conferences, experiments, preprints (SPIRES HEP), and even names and e-mail addresses of particle physicists.

B. Laboratories and accelerators

National and international high energy physics maintain extensive web pages with vast links to useful information. For a comprehensive listing, see http://www.nevis.columbia.edu/~quarknet/high_energy_physics_links.htm. Some examples are given in Tables 2 and 3.

Table 2: Major accelerator-based HEP laboratories and their public web pages.

Laboratory	Location	Web address
Brookhaven	Upton, New York, USA	http://www.bnl.gov/world/
Budker Inst.	Novosibirsk, Russia	http://www.inp.nsk.su/index.en.shtml
CERN	Geneva, Switz.	http://public.web.cern.ch/Public/
Cornell	Ithaca, New York, USA	http://www.lns.cornell.edu
DESY	Hamburg, Germany	http://www.desy.de/html/home/
Fermilab	Batavia, IL, USA	http://www.fnal.gov/
Frascati	Frascati, Italy	http://www.lnf.infn.it/
IHEP	Beijing, China	http://www.ihep.ac.cn/
IHEP	Protvino, Russia	http://www.ihep.su/
KEK	Tsukuba, Japan	http://www.kek.jp/intra.html
SLAC	Stanford, Calif., USA	http://www.slac.stanford.edu
TJNAF	Newport News, VA, USA	http://www.jlab.org/

The site <http://physics.web.cern.ch/Physics/HEPWebSites.html> contains a number of links to further web pages, including the CERN Large Hadron Collider at <http://lhc-new-homepage.web.cern.ch/lhc-new-homepage/>, the “Particle Adventure” site <http://particleadventure.org/particleadventure> of the Particle Data

Table 3: Major non-accelerator laboratories and their public web pages.

Laboratory	Location	Web address
Gran Sasso	Central Italy	http://www.lngs.infn.it/
Kamioka	Western Japan	http://www-sk.icrr.u-tokyo.ac.jp/
Soudan	Northern Minn.	http://www.hep.umn.edu/soudan/
Sudbury ν Obs.	Ontario	http://www.sno.phy.queensu.ca/

Group at Lawrence Berkeley National Laboratory, and *Quarknet*, a network for high school science teachers to involve them and their students in cutting-edge research in particle physics at <http://quarknet.fnal.gov/>. The IHEP laboratory in Russia hosts a chronology of particle physics discoveries: <http://ontil.ihep.su/~ppds/discovery.html>.

C. Popular article with extensive links

The **Scientific American** article on the future of particle physics by Steven Weinberg [132] appears on the web with a variety of links to other literature: <http://www.sciam.com/issue.cfm?issueDate=Dec-99>.

VIII. NOBEL PRIZES RELATED TO THE STANDARD MODEL

Some contributions in the past 45 years related to the formulation of the Standard Model that have been recognized by Nobel Prizes in Physics are summarized in Table 4. More information may be found on the web sites <http://www.slac.stanford.edu/library/nobel.html> and <http://www.nobel.se/physics/laureates>. Many additional prizes were awarded for instrumentation or discoveries crucial to our present understanding of the Standard Model.

IX. SNAPSHOT OF THE STANDARD MODEL

A. Quarks and leptons

The major ingredients of the Standard Model have been in place for some time, and can be gleaned from the popular article by Quigg [118]. The known building blocks of strongly interacting particles, the *quarks* [140, 141, 142], and the fundamental fermions lacking strong interactions, the *leptons*, are summarized in Table 5. The quark masses quoted there [73] are those for quarks probed at distances short compared with the characteristic size of strongly interacting particles. When regarded as constituents of strongly interacting particles, however, the *u* and *d* quarks act as quasi-particles with masses of about 0.3 GeV. The corresponding “constituent-quark” masses of *s*, *c*, and *b* are about 0.5, 1.5, and 4.9 GeV, respectively [52]. (For reviews of the spectroscopy of hadrons containing the heavy quarks *c* and *b*, see [50, 51, 53, 54].) The

Table 4: Nobel prizes in physics since 1957 related to the Standard Model.

Year	Recipient(s)	Subject
1957	T. D. Lee and C. N. Yang	Parity violation
1960	D. A. Glaser	Bubble chamber
1965	R. P. Feynman, J. S. Schwinger, and S. I. Tomonaga	Quantum electrodynamics
1968	L. W. Alvarez	Discovery of resonances
1969	M. Gell-Mann	Particle classification
1976	B. Richter and S. C. C. Ting	J/ψ discovery
1979	S. L. Glashow, A. Salam, and S. Weinberg	Electroweak unification
1980	J. W. Cronin and V. L. Fitch	CP violation
1982	K. G. Wilson	Critical phenomena
1984	C. Rubbia and S. Van Der Meer	W and Z discovery via $S\bar{p}pS$ collider
1988	L. M. Lederman, M. Schwartz, and J. Steinberger	Discovery that $\nu_\mu \neq \nu_e$
1990	J. I. Friedman, H. W. Kendall, and R. E. Taylor	Deep inelastic electron scattering
1992	G. Charpak	Particle detectors
1995	M. L. Perl F. Reines	τ lepton Neutrino detection
1999	G. 't Hooft and M. J. G. Veltman	Electroweak interactions
2002	R. Davis and M. Koshiba R. Giacconi	Cosmic neutrinos Cosmic X-rays

pattern of charge-changing weak transitions between quarks with charges $Q = 2/3$ and those with charges $Q = -1/3$ is described by the 3×3 *Cabibbo-Kobayashi-Maskawa* [143, 144], or *CKM* matrix; for a review of its properties, see [145].

The quarks and leptons in Table 5 fall into three “families.” For evidence that all the existing families (at least those containing light neutrinos) may have been discovered, see [128].

140. “A Schematic Model of Baryons and Mesons,” M. Gell-Mann, *Phys. Lett.* **8**, 214–215 (1964). (I)
141. “An $SU(3)$ Model for Strong Interaction Symmetry and its Breaking: 1,” G. Zweig, CERN report 8182/TH 401, 1964 (unpublished). Reprinted in **Developments in the Quark Theory of Hadrons**, edited by D. B. Lichtenberg and S. P. Rosen (Hadronic Press, Nonantum, MA, 1981), v. 1, pp. 22–101. (I)
142. “An $SU(3)$ Model for Strong Interaction Symmetry and its Breaking: 2,” G.

Table 5: The known quarks and leptons. Masses in GeV except where indicated otherwise. Here and elsewhere $c = 1$.

Quarks			Leptons				
Charge 2/3		Charge -1/3	Charge -1		Charge 0		
Mass		Mass	Mass		Mass		
u	0.0015–0.0045	d	0.005–0.0085	e	0.000511	ν_e	< 3 eV
c	1.0–1.4	s	0.085–0.155	μ	0.106	ν_μ	< 190 keV
t	174.3 ± 5.1	b	4.0–4.5	τ	1.777	ν_τ	< 18.2 MeV

Zweig, CERN report 8419/TH 412, 1964 (unpublished). Reprinted in **Developments in the Quark Theory of Hadrons**, edited by D. B. Lichtenberg and S. P. Rosen (Hadronic Press, Nonantum, MA, 1980), v. 1, pp. 22–101. (I)

143. “Unitary Symmetry and Leptonic Decays,” N. Cabibbo, Phys. Rev. Lett. **10**, 531–532 (1963). (I)
144. “CP Violation in the Renormalizable Theory of Weak Interaction,” M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652–657 (1973). (I)
145. “The Cabibbo-Kobayashi-Maskawa Quark-Mixing Matrix,” F. J. Gilman, K. Kleinknecht, and B. Renk, in **Review of Particle Physics**, K. Hagiwara *et al.* [73], pp. 113–119.

B. Gauge theories

A theory of particles and their interactions permitting arbitrary changes of phase in the particle’s quantum mechanical state is an *Abelian local gauge theory* such as electromagnetism. The term “Abelian” indicates that gauge (phase) transformations at a given space-time point commute with one another, while “local” stands for the freedom to make separate gauge transformations at each space-time point. The name “gauge” originated with Hermann Weyl [146].

Gauge transformations may be generalized to those that do *not* commute with one another at a given space-time point. The first such *non-Abelian* gauge theory was proposed by C. N. Yang and R. L. Mills [147], who used it to describe the strong interactions through self-interacting mesons of spin 1 carrying isospin.

The review by Abers and Lee [48] helped a generation of physicists to apply gauge theories to the electroweak and strong interactions. An excellent introduction to the subject at the intermediate graduate level is given by Quigg [18]. An article addressed to the lay reader has been written by ’t Hooft [111]. A recent text [148] provides a further introduction to the subject.

146. “Electron and Gravitation [in German],” H. Weyl, Z. Phys. **56**, 330–352 (1929), partially reprinted in Surveys in High Energy Phys. **5**, 261–267 (1986). (A)

147. “Conservation of Isotopic Spin and Isotopic Gauge Invariance,” C. N. Yang and R. L. Mills, Phys. Rev. **96**, 191–195 (1954). (A) See also Cambridge University Dissertation, R. Shaw, 1954 (unpublished).
148. **The Dawning of Gauge Theory**, L. O’Raifeartaigh (Princeton University Press, 1997). (I)

C. Color and quantum chromodynamics

The quarks are distinguished from the leptons by possessing a three-fold charge known as “color” that enables them to interact strongly with one another [149, 150, 151]. We also speak of quark and lepton “flavor” when distinguishing the particles in Table 5 from one another. The evidence for color comes from several quarters.

1. *Quark statistics.* The Δ^{++} , a low-lying excited state of the nucleon, can be represented in the quark model as uuu , so it is totally symmetric in flavor. It has spin $J = 3/2$, a totally symmetric combination of the three $J = 1/2$ quark spins. As a ground state, its spatial wave function should be symmetric as well. While a state composed of fermions should be totally *antisymmetric* under the interchange of any two fermions, the state described so far is totally *symmetric* under the product of flavor, spin, and space interchanges. Color introduces an additional degree of freedom under which the interchange of two quarks can produce a minus sign.

2. *Electron-positron annihilation to hadrons.* The charges of all quarks that can be produced in pairs at a given center-of-mass energy is measured by the ratio $R \equiv \sigma(e^+e^- \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \mu^+\mu^-) = \sum_i Q_i^2$, where Q_i is the charge of quark i in units of $|e|$. Measurements [73] indicate values of R in various energy ranges consistent with $N_c = 3$ (with a small positive correction associated with the strong interactions of the quarks).

3. *Neutral pion decay.* The π^0 decay rate is governed by a quark loop diagram in which two photons are radiated by the quarks in $\pi^0 = (u\bar{u} - d\bar{d})/\sqrt{2}$. The predicted rate is $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.6S^2 \text{ eV}$, where $S = N_c(Q_u^2 - Q_d^2) = N_c/3$. The experimental rate is $7.8 \pm 0.6 \text{ eV}$, in accord with experiment if $S = 1$ and $N_c = 3$.

4. *Triality.* Quark composites appear only in multiples of three. Baryons are composed of qqq , while mesons are $q\bar{q}$ (with total quark number zero). This is compatible with our current understanding of QCD, in which only color-singlet states can appear in the spectrum.

A crucial feature of the QCD theory of strong interactions is its “asymptotic freedom,” a weakening interaction strength at short distances permitting the interpretation of deep inelastic scattering experiments [96, 152, 153] in terms of quarks. This property was found to be characteristic of non-Abelian gauge theories such as color SU(3) by Gross and Wilczek [154, 155, 156] and by Politzer [157, 158]. The result was obtained earlier for the gauge group SU(2) by Khriplovich [159] (see also [160]), but its significance for a strong-interaction theory was not realized then.

Direct evidence for the quanta of QCD, the gluons, was first presented in 1979 on the basis of extra “jets” of particles produced in electron-positron annihilations to hadrons. Normally one sees two clusters of energy associated with the fragmentation of each quark in $e^+e^- \rightarrow q\bar{q}$ into hadrons. However, in some fraction of events an

extra jet was seen, corresponding to the radiation of a gluon by one of the quarks. For a popular history of this discovery, containing further references, see [96].

The transformations that take one color of quark into another are those of the group $SU(3)$. This group is called $SU(3)_{\text{color}}$ to distinguish it from the $SU(3)_{\text{flavor}}$ associated with the quarks u , d , and s .

149. “Spin and Unitary Spin Independence in a Paraquark Model of Baryons and Mesons,” O. W. Greenberg, *Phys. Rev. Lett.* **13**, 598–602 (1964). (I)
150. Y. Nambu, “A Systematics of Hadrons in Subnuclear Physics,” in **Preludes in Theoretical Physics in Honor of V. F. Weisskopf**, edited by A. De-Shalit, H. Feshbach, and L. Van Hove (North-Holland, Amsterdam and Wiley, New York, 1966), pp. 133–42. (A)
151. “Advantages of the Color Octet Gluon Picture,” H. Fritzsch, M. Gell-Mann, and H. Leutwyler, *Phys. Lett.* **47B**, 365–368 (1973). (I)
152. “High-Energy Inelastic ep Scattering at 6° and 10° ,” E. D. Bloom *et al.*, *Phys. Rev. Lett.* **23**, 930–934 (1969). (I)
153. “Observed Behavior of Highly Inelastic Electron–Proton Scattering,” M. Breidenbach *et al.*, *Phys. Rev. Lett.* **23**, 935–939 (1969). (I)
154. “Ultraviolet Behavior of Non-Abelian Gauge Theories,” D. J. Gross and F. Wilczek, *Phys. Rev. Lett.* **30**, 1343–1346 (1973). (A)
155. “Asymptotically Free Gauge Theories. I,” D. J. Gross and F. Wilczek, *Phys. Rev. D* **8**, 3633–3652 (1973). (A)
156. “Asymptotically Free Gauge Theories. 2,” D. J. Gross and F. Wilczek, *Phys. Rev. D* **9**, 980–993 (1974). (A)
157. “Reliable Perturbative Results for Strong Interactions?,” H. David Politzer, *Phys. Rev. Lett.* **30**, 1346–1349 (1973). (A)
158. “Asymptotic Freedom: An Approach to Strong Interactions,” H. David Politzer, *Phys. Rep.* **14**, 129–180 (1974). (A)
159. “Green’s Functions in Theories with Non-Abelian Gauge Group,” I. B. Khriplovich, *Yad. Fiz.* **10**, 409–424 (1969) [*Sov. J. Nucl. Phys.* **10**, 235–242 (1969)]. (A)
160. “Renormalization of Gauge Theories,” G. ’t Hooft, in [85], pp. 179–198. (A)

D. Weak interactions

The electromagnetic interaction is described in terms of photon exchange. The quantum electrodynamics of photons and electrons initially encountered divergent quantities tamed in the 1940s through *renormalization*, leading to successful estimates

of the anomalous magnetic moment of the electron and the Lamb shift in hydrogen [86]. By contrast, the weak interactions as formulated up to the mid-1960s involved the pointlike interactions of two currents. This interaction is very singular and cannot be renormalized. The weak currents in this theory were purely charge-changing. As a result of work by Gershtein and Zel'dovich (who suggested that the weak vector current is of universal strength) [161], Lee and Yang [162, 163, 164], Feynman and Gell-Mann [165], and Sudarshan and Marshak [166], the weak currents were identified as having (vector)–(axial) or “ $V - A$ ” form.

- 161. “Meson Corrections in the Theory of Beta Decay,” S. S. Gershtein and Ia. B. Zel'dovich, *Zh. Eksp. Teor. Fiz.* **29**, 698–699 (1955) [*Sov. Phys. - JETP* **2**, 576–578 (1956)]. (A)
- 162. “Question of Parity Conservation in Weak Interactions,” T. D. Lee and C. N. Yang, *Phys. Rev.* **104**, 254–258 (1956). (A)
- 163. “Parity Nonconservation and a Two Component Theory of the Neutrino,” T. D. Lee and C. N. Yang, *Phys. Rev.* **105**, 1671–1675 (1957). (A)
- 164. “Remarks on Possible Noninvariance Under Time Reversal and Charge Conjugation,” T. D. Lee, R. Oehme, and C. N. Yang, *Phys. Rev.* **106**, 340–345 (1957). (A)
- 165. “Theory of the Fermi Interaction,” R. P. Feynman and M. Gell-Mann, *Phys. Rev.* **109**, 193–198 (1958). (I)
- 166. “Chirality Invariance and the Universal Fermi Interaction,” E. C. G. Sudarshan and R. E. Marshak, *Phys. Rev.* **109**, 1860–1862 (1958). (A)

E. Electroweak unification

Yukawa [167] and Klein [168] proposed early boson-exchange models for the charge-changing weak interactions. Klein’s model had self-interacting bosons, thus anticipating the theory of Yang and Mills [147]. Schwinger and others studied such models in the 1950s, but Glashow [169] realized that a new *neutral* heavy boson Z , in addition to the massless photon and massive charged bosons, was needed to successfully unify the weak and electromagnetic interactions. The use of the Higgs [170, 171, 172, 173] mechanism to break the electroweak symmetry by Weinberg [174] and Salam [175] converted this phenomenological theory into one suitable for higher-order calculations.

The charge-changing weak currents could be viewed as members of an $SU(2)$ algebra [176, 143]. However, the neutral member of this multiplet could not be identified with electric charge. Charged W^\pm bosons couple only to left-handed fermions, while the photon couples to both left and right-handed fermions. Moreover, a theory with only photons and charged weak bosons leads to unacceptable divergences in higher-order processes [18]. The neutral heavy Z boson can be arranged to cancel these divergences. It leads to *neutral current interactions*, in which (for example) an incident neutrino scatters inelastically on a hadronic target without changing its charge.

The discovery of neutral-current interactions of neutrinos [177, 178, 179, 180] and other manifestations of the Z strikingly confirmed the new theory.

A key stumbling block to the construction of an electroweak theory applying to the quarks known at the time (u , d , and s) was the presence of *flavor-changing neutral currents*. The hypothesis of a fourth “charmed” quark c was an elegant way to avoid this problem [181]. The charmed quark also was crucial in avoiding “anomalies,” effects due to triangle diagrams involving internal fermions and three external gauge bosons [182, 183, 184]. Evidence for charm was first found in 1974 in the form of the J/ψ particle [185, 186], a bound state of c and \bar{c} . An earlier Resource Letter [75] deals with events leading up to this discovery, as well as early evidence for the fifth (b) quark to be mentioned below. The whole topic of electroweak unification is dealt with at an intermediate level in several references mentioned earlier (e.g., [14, 18, 24]).

167. “On the Interaction of Elementary Particles,” H. Yukawa, Proc. Phys. Math. Soc. Japan **17**, 48–57 (1935). (A)
168. “Sur la Théorie des Champs Associés à des Particules Chargées,” O. Klein, in **Les Nouvelles Théories de la Physique**, Paris, Inst. de Coöperation Intellectuelle (1939), pp. 81–98, translation “On the Theory of Charged Fields,” reprinted in **Oskar Klein Memorial Lectures** vol. 1, edited by G. Ekspong (World Scientific, Singapore, 1991), and in *Surveys in High Energy Phys.* **5**, 269–285 (1986). (A)
169. “Partial Symmetries of Weak Interactions,” S. L. Glashow, Nucl. Phys. **22**, 579–588 (1961). (A)
170. “Broken Symmetries, Massless Particles, and Gauge Fields,” P. W. Higgs, Phys. Lett. **12**, 132–133 (1964). (A)
171. “Broken Symmetries and the Masses of Gauge Bosons,” P. W. Higgs, Phys. Rev. Lett. **13**, 508–509 (1964). (A)
172. “Broken Symmetry and the Mass of Gauge Vector Mesons,” F. Englert and R. Brout, Phys. Rev. Lett. **13**, 321–322 (1964). (A)
173. “Global Conservation Laws and Massless Particles,” G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Phys. Rev. Lett. **13**, 585–587 (1964). (A)
174. “A Model of Leptons,” S. Weinberg, Phys. Rev. Lett. **19**, 1264–1266 (1967). (A)
175. “Weak and Electromagnetic Interactions,” A. Salam, in **Proceedings of the Eighth Nobel Symposium**, edited by N. Svartholm (Almqvist and Wiksell, Stockholm, 1968; Wiley, New York, 1978), pp. 367–377. (A)
176. “The Axial Vector Current in Beta Decay,” M. Gell-Mann and M. Lévy, Nuovo Cim. **16**, 705–726 (1960). (I)

- 177. “Search for Elastic Muon Neutrino Electron Scattering,” F. J. Hasert *et al.*, Phys. Lett. B **46B**, 121–124 (1973). (I)
- 178. “Observation of Neutrino-Like Interactions Without Muon or Electron in the Gargamelle Neutrino Experiment,” F. J. Hasert *et al.*, Phys. Lett. **46B**, 138–140 (1973). (I)
- 179. “Observation of Neutrino-Like Interactions Without Muon or Electron in the Gargamelle Neutrino Experiment,” F. J. Hasert *et al.*, Nucl. Phys. **B73**, 1–22 (1974). (I)
- 180. “Observation of Muonless Neutrino Induced Inelastic Interactions,” A. C. Benvenuti *et al.*, Phys. Rev. Lett. **32**, 800–803 (1974). (I)
- 181. “Weak Interactions with Lepton-Hadron Symmetry,” S. L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D **2**, 1285–1292 (1970). (I)
- 182. “An Anomaly Free Version of Weinberg’s Model,” C. Bouchiat, J. Iliopoulos, and P. Meyer, Phys. Lett. **38B**, 519–523 (1972). (I)
- 183. “Gauge Theories Without Anomalies,” H. Georgi and S. L. Glashow, Phys. Rev. D **6**, 429–431 (1972). (I)
- 184. “Effect of Anomalies on Quasi-Renormalizable Theories,” D. J. Gross and R. Jackiw, Phys. Rev. D **6**, 477–493 (1972). (A)
- 185. “Experimental Observation of a Heavy Particle J ,” J. J. Aubert *et al.*, Phys. Rev. Lett. **33**, 1404–1406 (1974). (I)
- 186. “Discovery of a Narrow Resonance in e^+e^- Annihilation,” J. E. Augustin *et al.*, Phys. Rev. Lett. **33**, 1406–1408 (1974). (I)

F. CP violation

The symmetries of time reversal (T), charge conjugation (C), and space inversion or parity (P) have provided both clues and puzzles in our understanding of the fundamental interactions. The realization that the charge-changing weak interactions violated P and C maximally was central to the formulation of the $V - A$ theory. The theory was constructed in 1957 to conserve the product CP, but the discovery in 1964 of the long-lived neutral kaon’s decay to two pions ($K_L \rightarrow \pi\pi$) [187] showed that even CP was not conserved. In 1973, Kobayashi and Maskawa (KM) [144] proposed that CP violation in the neutral kaon system could be explained in a model with three families of quarks. The quarks of the third family, now denoted by b for bottom and t for top, were subsequently discovered in 1977 [188, 189] and 1994 [190, 191, 192, 193, 194, 195], respectively. Popular articles on these discoveries include one by Lederman [110] and Liss and Tipton [129].

An alternative theory of CP violation in the kaon system, proposed by Wolfenstein [196], involved a “superweak” CP-violating interaction mixing K^0 and \bar{K}^0 , which

would lead to identical CP violation in $K_L \rightarrow \pi^+\pi^-$ and $K_L \rightarrow \pi^0\pi^0$. The discovery that this was not so (see [197, 198] for the most recent published results, which are continually being updated in conference reports) disproved the superweak theory and displayed a “direct” form of CP violation with magnitude consistent with that predicted by the KM theory.

Decays of hadrons containing b quarks are further ground for testing the KM hypothesis and for displaying evidence for new physics beyond this “standard model” of CP violation. A meson containing a \bar{b} quark will be known generically as a B meson. Electron-positron colliders have been constructed at SLAC (Stanford, CA) [199] and KEK (Tsukuba, Japan) [200] expressly to study B mesons; others at DESY (Hamburg, Germany) and Cornell (Ithaca, NY) [201] were fortunate in having just the right energy to produce B mesons in pairs. The BaBar detector at SLAC and the Belle detector at KEK have already produced a series of major results on B decays and CP violation [202, 203]. Studies of particles containing b quarks also are expected to be an important part of the physics program at the Fermilab Tevatron [204] and the CERN Large Hadron Collider (LHC) [205].

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196. “Violation of CP Invariance and the Possibility of Very Weak Interactions,” L. Wolfenstein, *Phys. Rev. Lett.* **13**, 562–564 (1964). (I)

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200. “KEKB Performance,” Belle Collaboration, presented by A. E. Bondar at Beauty-2000: 7th International Conference on B-Physics at Hadron Machines, Sea of Galilee, Kibbutz Maagan, Israel, 13–18 Sept. 2000, Nucl. Instr. Meth. A **462**, 139–145 (2001). (I)
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202. “Measurement of the CP-violating Asymmetry Amplitude $\sin(2\beta)$,” BaBar Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **89**, 201802 (2002). (I)
203. “An Improved Measurement of Mixing-Induced CP Violation in the Neutral B Meson System,” Belle Collaboration, K. Abe *et al.*, Phys. Rev. D **66**, 071102(R) (2002). (I)
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G. Dynamics of heavy quarks

With the discovery of the charmed (Sec. IX E) and beauty (Sec. IX F) quarks, a whole new laboratory emerged for the study of QCD. A bound state of a heavy quark and its antiquark, $c\bar{c}$ or $b\bar{b}$, is known as *quarkonium*, in analogy with positronium, the bound state of a positron and an electron. (The top quark lives too short a time for $t\bar{t}$ bound states to be of much interest, though one can study some effects of the binding.) Quarkonium states have been extensively studied, [50, 51, 53, 54],

with their spectroscopy and decays providing useful information on QCD at various distance scales.

The states of light quarks bound to a single heavy quark have their own regularities. They are analogous to atoms in which the light quarks and gluons represent the “electronic” degrees of freedom, while the heavy quarks represent the nuclei. Thus, certain properties of these states are related in the same way that, for example, properties of hydrogen and deuterium are related. This “heavy quark symmetry” [55] has provided very useful guides to the properties of hadrons containing charm and beauty quarks, and permits more precise determinations of underlying weak couplings (such as elements of the Cabibbo-Kobayashi-Maskawa [CKM] matrix).

H. Higgs boson(s)

An unbroken $SU(2) \otimes U(1)$ theory involving the photon would require *all* fields to have zero mass, whereas the W^\pm and Z are massive. The symmetry-breaking that generates W and Z masses must not destroy the renormalizability of the theory. The *Higgs mechanism* achieves this goal at the price of introducing an additional degree of freedom corresponding to a physical particle, the *Higgs particle*, which is the subject of intense searches [32, 120, 206, 207]. Current 95% c.l. limits on a standard-model Higgs boson are $M_H > 114 \text{ GeV}/c^2$ via direct searches [208] and $M_H < 193 \text{ GeV}/c^2$ from fits to precise electroweak data [209].

Discovering the nature of the Higgs boson is a key to further progress in understanding what may lie beyond the Standard Model. There may exist one Higgs boson or more than one. There may exist other particles in the spectrum related to it. The Higgs boson may be elementary or composite. If composite, it points to a new level of substructure of the elementary particles.

I. Precision electroweak measurements

Precision electroweak measurements can yield information on many new-physics possibilities in addition to the Higgs boson. The seminal paper of Veltman [210] showed how the ratio of W and Z masses could shed light on the top quark’s mass. A systematic study of electroweak radiative corrections within the Standard Model was performed by Marciano and Sirlin [211] and used to analyze a wide variety of electroweak data, initially in [212] and most recently in [209]. Widely-used parametrizations of deviations from Standard-Model predictions [213, 214, 215] have been used to constrain new particles in higher-order loop diagrams associated with W , Z , and photon self-energies. Some reviews include Refs. [216, 217, 218, 219].

- 206. “Report of the Tevatron Higgs Working Group,” M. Carena *et al.*, Fermilab report FERMILAB-CONF-00-279-T, hep-ph/0010338 (unpublished). (A)
- 207. “The Higgs Working Group: Summary Report,” D. Cavalli *et al.*, in Proceedings of Workshop on Physics at TeV Colliders, Les Houches, France, 21 May – 1 June 2001, edited by P. Aurenche *et al.* (Paris, IN2P3, 2001), pp. 1–120. (A)

208. LEP Higgs Working Group, results quoted in web page of LEP Electroweak Working Group, <http://lepewwg.web.cern.ch/LEPEWWG/>. (I)
209. LEP Electroweak Working Group, <http://lepewwg.web.cern.ch/LEPEWWG/>. (I)
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214. “Estimation of Oblique Electroweak Corrections,” M. E. Peskin and T. Takeuchi, Phys. Rev. D **46**, 381–409 (1992). (A)
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216. “Electroweak Theory. Framework of On-Shell Renormalization and Study of Higher-Order Effects,” K. I. Aoki *et al.*, Prog. Theor. Phys. Suppl. **73**, 1–225 (1982). (A)
217. “Electroweak Radiative Corrections, M_Z , M_W , and the Heavy Top,” W. Hollik, Adv. Ser. Direct. High Energy Phys. **10**, 1–57 (1992). (A)
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219. “Radiative Corrections in Gauge Theories,” H. Anlauf, lectures at Adriatic School on Particle Physics and Physics Informatics, September 11–21, 2001, <http://hepplix.ikp.physik.tu-darmstadt.de/~anlauf/ha-lectures.html>. (A)

X. PROPOSED EXTENSIONS

A. Supersymmetry

Unification of the electroweak and strong interactions at a high mass scale leads to the *hierarchy problem*, in which this scale contributes through loop diagrams to the Higgs boson mass and requires it to be fine-tuned at each order of perturbation theory.

A similar problem is present whenever there is a large gap between the electroweak scale and *any* higher mass scale contributing to the Higgs boson mass. *Supersymmetry* solves this problem by introducing for each particle of spin J a *superpartner* of spin $J \pm 1/2$ whose contribution to such loop diagrams cancels the original one in the limit of degenerate masses. Recent reviews of supersymmetry and its likely experimental signatures include [40, 62, 63, 64, 65, 66, 67], while earlier discussions are given by [68], [69], and [70]. For an article at the popular level see [119].

B. Dynamical electroweak symmetry breaking

If the Higgs boson is not fundamental but arises as the result of a new super-strong force which, in analogy with color, causes the *dynamical* generation of one or more scalar particles, the hierarchy problem can be avoided. This scheme, sometimes called “technicolor,” was proposed in the 1970s [220, 221, 222]. For recent reviews, see. e.g., [223, 224, 225].

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- 221. “Implications of Dynamical Symmetry Breaking: An Addendum,” S. Weinberg, Phys. Rev. D **19**, 1277–1280 (1979). (A)
- 222. “Dynamics of Spontaneous Symmetry Breaking in the Weinberg-Salam Theory,” L. Susskind, Phys. Rev. D **20**, 2619–2625 (1979). (A)
- 223. “Lectures on Technicolor and Compositeness,” R. S. Chivukula, in [47], pp. 731–772. (A)
- 224. “Two Lectures on Technicolor,” K. Lane, Fermilab report FERMILAB-PUB-02-040-T, preprint hep-ph/0202255 (unpublished). (A)
- 225. “Strong dynamics and electroweak symmetry breaking,” C. T. Hill and E. H. Simmons, Fermilab report FERMILAB-PUB-02-045-T, preprint hep-ph/0203079, submitted to Physics Reports. (A)

C. Fermion mass and mixing patterns

The transitions between the (u, c, t) and (d, s, b) quarks owing to virtual W emission or absorption are described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix mentioned in Sec. IX A. (For one parametrization of this matrix see [226].) The CKM matrix arises because the matrices that diagonalize the mass matrices of (u, c, t) and of (d, s, b) are not the same. A theory of quark masses would thus entail a specific form of the CKM matrix. For the corresponding matrix for leptons, see [227, 228, 229]. While a theory of quark and lepton masses still eludes us, attempts have been made to guess some of its general features [230, 231, 232, 233, 234, 235].

226. “Parametrization of the Kobayashi-Maskawa Matrix,” L. Wolfenstein, *Phys. Rev. Lett.* **51**, 1945–1947 (1983). (I)
227. “Remarks on the Unified Model of Elementary Particles,” Z. Maki, M. Nakagawa, and S. Sakata, *Prog. Theor. Phys.* **28**, 870–880 (1962). (A)
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230. “Weak Interaction Mixing in the Six-Quark Theory,” H. Fritzsch, *Phys. Lett.* **B73**, 317–322 (1978). (I)
231. “Hierarchy of Quark Masses, Cabibbo Angles, and CP Violation,” C. D. Froggatt and H. B. Nielsen, *Nucl. Phys.* **B147**, 277–298 (1979). (A)
232. “Unified Theories With $U(2)$ Flavor Symmetry,” R. Barbieri, L. J. Hall, S. Raby, and A. Romanino, *Nucl. Phys.* **B493**, 3–26 (1997). (A)
233. “A model for Fermion Mass Hierarchies and Mixings,” P. Ramond, in **Particles, Strings, and Cosmology (PASCOS 98)**, Proceedings of the 6th International Symposium on Particles, Strings and Cosmology, Boston, MA, 22–27 Mar. 1998, edited by P. Nath (World Scientific, Singapore, 1999), pp. 567–577. (A)
234. “Mass and flavor mixing schemes of quarks and leptons,” H. Fritzsch and Z.-z. Xing, *Prog. Part. Nucl. Phys.* **45**, 1–81 (2000). (A)
235. “GUT model predictions for neutrino oscillation parameters compatible with the large mixing angle MSW solution,” C. H. Albright and S. Geer, *Phys. Rev. D* **65**, 073004 (2002), and Refs. [11] and [15] therein. (A)

D. Composite quarks and leptons

Families of quarks and leptons appear to be replicas of one another (see Table 5), aside from their differing masses and weak couplings. Attempts have been made to explain this regularity in terms of a composite structure, much as the periodic table of the elements reflects their underlying atomic structure. A set of guidelines for this program was laid down by 't Hooft [236]. For an example of a recent effort, see [237].

236. “Naturalness, chiral symmetry, and spontaneous chiral symmetry breaking,” G. 't Hooft, in **Recent Developments in Gauge Theories** (Cargèse Summer Institute, Aug. 26 - Sept. 8, 1979), edited by G. 't Hooft *et al.* (Plenum, New York, 1980), pp. 135–157. (A)

237. “Composite quarks and leptons from dynamical supersymmetry breaking without messengers,” N. Arkani-Hamed, M. A. Luty, and J. Terning, *Phys. Rev. D* **58**, 015004 (1998). (A)

E. Grand unification and extended gauge groups

An early point in favor of quark–lepton unification was the anomaly cancellation [182, 183, 184] mentioned in Sec. IX E. The idea that lepton number could be regarded as a fourth “color,” leading to an extended gauge group embracing both electroweak and strong interactions, was proposed by Pati and Salam [238].

The strong and electroweak coupling constants are expected to approach one another at very small distance (large momentum) scales [239], suggesting *grand unified theories* based on symmetry groups such as $SU(5)$ [240], $SO(10)$ [241], and E_6 [242]. (For an early popular article on this program see [114].) These theories typically predict that the proton will decay [115, 116, 117], and some of them entail additional observable gauge bosons besides those of the $SU(3) \times SU(2) \times U(1)$ Standard Model [71]. Some useful group-theoretic techniques for model-building are described in [56].

238. “Unified Lepton–Hadron Symmetry and a Gauge Theory of the Basic Interactions,” J. C. Pati and A. Salam, *Phys. Rev. D* **8**, 1240–1251 (1973). See also “Is Baryon Number Conserved?,” J. C. Pati and A. Salam, *Phys. Rev. Lett.* **31**, 661–664 (1973); “Lepton Number as the Fourth Color,” J. C. Pati and A. Salam, *Phys. Rev. D* **10**, 275–289 (1974). (A)
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240. “Unity of All Elementary Particle Forces,” H. Georgi and S. L. Glashow, *Phys. Rev. Lett.* **32**, 438–441 (1974). (I)
241. “The State of the Art — Gauge Theories,” H. Georgi, in **Particles and Fields — 1974**, Proceedings of the Williamsburg Meeting, Sept. 5–7, 1974, edited by C. E. Carlson (AIP Conf. Proc. No. 23) (AIP, New York, 1975), pp. 575–582. (A)
242. “A Universal Gauge Theory Model Based on E_6 ,” F. Gürsey, P. Ramond, and P. Sikivie, *Phys. Lett.* **60B**, 177–180 (1976). (A)

F. Strong CP problem and axions

In a non-abelian gauge theory such as $SU(3)$ there can arise non-trivial gauge configurations that prevent terms in the Lagrangian proportional to $\text{Tr}(G_{\mu\nu}\tilde{G}^{\mu\nu})$ from being ignored as pure divergences. Such terms can lead to strong CP violation. Their coefficient, a parameter conventionally called θ , must be of order 10^{-10} or smaller in order not to conflict with limits on the electric dipole moment of the neutron [243]. Several proposals have been advanced for why θ is so small [40, 244]. In one of the most interesting, θ is promoted to the status of a dynamical variable that can relax

to a natural value of zero. As a consequence, there arises a nearly massless particle known as the *axion*, whose properties (and the search for which) are well-described in [40, 244].

243. “New Experimental Limit on the Electric Dipole Moment of the Neutron,” P. G. Harris *et al.*, Phys. Rev. Lett. **82**, 904–907 (1999). (I)

244. “The Strong CP Problem,” M. Dine, in [47], pp. 349–369.

G. String theory

A truly unified theory of interactions must include gravity. The leading candidate for such a theory is *string theory*, which originated in pre-QCD attempts to explain the strong interactions [245, 246, 247, 248] by replacing the space-time points of quantum field theories with extended objects (“strings”). In 1974 it was realized that string theories necessarily entailed a massless spin-2 particle, for which the graviton was an ideal candidate [249]. While it appeared that such theories required space-time to be 26-dimensional (or 10-dimensional in the presence of supersymmetry), these extra dimensions were interpreted in the 1980s as a source of the internal degrees of freedom characterizing particle quantum numbers (see. e.g., [250, 251, 252]). A typical scenario whereby string theory might yield predictions for the quark and lepton spectrum is described in [253].

Early results on string theory are described in the textbook by Green, Schwarz, and Witten [41, 42]. Later texts are [43, 44]. Descriptions for the non-specialist are given by Green [122], Duff [123], Greene [100] and Weinberg [132].

245. Y. Nambu, “Quark Model and the Factorization of the Veneziano Amplitude,” in **Symmetries and Quark Models: Proceedings** (International Conference on Symmetries and Quark Models, Detroit, Mich., June 1969), edited by R. Chand (Gordon and Breach, New York, 1970), pp. 269–277. (A)

246. “A General Treatment of Factorization in Dual Resonance Models,” S. Fubini, D. Gordon, and G. Veneziano, Phys. Lett. **29B**, 670–682 (1969). (A)

247. “Dual Symmetric Theory of Hadrons. 1,” L. Susskind, Nuovo Cim. **A69**, 457–496 (1970). (A)

248. “Strings, Monopoles, and Gauge Fields,” Y. Nambu, Phys. Rev. D **10**, 4262–4268 (1974). (A)

249. “Dual Models for Nonhadrons,” J. Scherk and J. H. Schwarz, Nucl. Phys. **B81**, 118–144 (1974). (A)

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252. “Heterotic String Theory. 2. The Interacting Heterotic String,” D. J. Gross, J. A. Harvey, E. Martinec, and R. Rohm, *Nucl. Phys.* **B267**, 75–124 (1986). (A)
253. “Vacuum Configurations for Superstrings,” P. Candelas, G. T. Horowitz, A. Strominger, and E. Witten, *Nucl. Phys.* **B258**, 46–74 (1985). (A)

H. Large extra dimensions

Although the usual superstring scenario envisions the six extra dimensions in such theories as having spatial extent of the order of the Planck scale, $(G_N \hbar / c^3)^{1/2} \simeq 10^{-33}$ cm, theories have been proposed in which some of the extra dimensions are larger, leading to observable effects at accelerators or in precise tests of Newton’s universal inverse square law of gravitation [254, 255, 256, 257, 258]. Reviews for the non-specialist have appeared in *Scientific American* [137] and *Physics Today* [138].

254. “A Possible New Dimension at a Few TeV,” I. Antoniadis, *Phys. Lett. B* **246**, 377–384 (1990). (A)
255. “Weak Scale Superstrings,” J. D. Lykken, *Phys. Rev. D* **54**, R3693–R3697 (1996). (A)
256. “The Hierarchy Problem and New Dimensions at a Millimeter,” N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, *Phys. Lett. B* **429**, 263–272 (1998). (A)
257. “New Dimensions at a Millimeter to a Fermi and Superstrings at a TeV,” I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, *Phys. Lett. B* **436**, 257–263 (1998). (A)
258. “Phenomenology, Astrophysics and Cosmology of Theories with Sub-Millimeter Dimensions and TeV Scale Quantum Gravity,” N. Arkani-Hamed, S. Dimopoulos, and G. R. Dvali, *Phys. Rev. D* **59**, 086004 (1999). (A)

XI. HINTS OF NEW PHYSICS

A. Neutrino masses

The ability of neutrinos of one species to undergo oscillations into another is an indication of non-zero and non-degenerate neutrino masses [57, 58]. Several experiments find evidence for such oscillations. Reviews have appeared in [59, 61, 131]; the second of these also deals with precision electroweak tests using neutrinos.

1. Solar neutrinos:

Since the earliest attempts to detect neutrinos originating from the Sun in the mid-1960s, the flux has been less than predicted in the standard solar model [125]. Recent experiments at the Sudbury Neutrino Observatory (SNO) in Ontario [259, 260] and the KamLAND experiment in Japan [261] strongly suggest that this deficit is due to oscillations of the electron neutrinos produced in the Sun into other species, most

likely a combination of muon and tau neutrinos, induced by interaction with the Sun in a manner (now known as the MSW effect) first proposed by Mikheev and Smirnov [262] and Wolfenstein [263]. For reviews, see [35, 60].

2. Atmospheric neutrinos:

Neutrinos produced by the interactions of cosmic rays in the atmosphere are expected to be in the ratio $\nu_\mu : \nu_e = 2 : 1$ (summing over neutrinos and antineutrinos) [264]. Instead, a ratio more like 1:1 is observed. This phenomenon has been traced to oscillations that are most likely $\nu_\mu \rightarrow \nu_\tau$, as a result of definitive experiments performed by the Super-Kamiokande Collaboration in Japan [265, 266]. The mixing appears to be close to maximal, in contrast to the small mixings of quarks described by off-diagonal elements of the CKM matrix.

3. Indications in an accelerator experiment:

An experiment performed at Los Alamos National Laboratory [267] in the Liquid Scintillator Neutrino Detector (LSND) finds evidence for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations. An experiment known as MiniBooNE which has begun to operate at Fermilab will check this possibility [268].

259. “Measurement of the Charged Current Interactions Produced by ^8B Solar Neutrinos at the Sudbury Neutrino Observatory,” SNO Collab., Q. R. Ahmad *et al.*, Phys. Rev. Lett. **87**, 071301 (2001). (I)
260. “Direct Evidence for Neutrino Flavor Transformation from Neutral-Current Interactions in the Sudbury Neutrino Observatory,” SNO Collab., Q. R. Ahmad *et al.*, Phys. Rev. Lett. **89**, 011301 (2002); “Measurement of Day and Night Neutrino Energy Spectra at SNO and Constraints on Neutrino Mixing Parameters,” SNO Collab., Q. R. Ahmad *et al.*, Phys. Rev. Lett. **89**, 011302 (2002). (I)
261. “First Results from KamLAND: Evidence for Reactor Anti-Neutrino Disappearance,” KamLAND Collaboration, K. Eguchi *et al.*, preprint hep-ex/0212021, submitted to Phys. Rev. Letters. (I)
262. “Resonance Enhancement of Oscillations in Matter and Solar Neutrino Spectroscopy,” S. P. Mikheev and A. Yu. Smirnov, Yad. Fiz. **42**, 1441–1448 (1985) [Sov. J. Nucl. Phys. **42**, 913–917 (1985)]. (I)
263. “Neutrino Oscillations in Matter,” L. Wolfenstein, Phys. Rev. D **17**, 2369–2374 (1978). (I)
264. “Flux of Atmospheric Neutrinos,” T. K. Gaisser and M. Honda, preprint hep-ph/0203272, to appear in Ann. Rev. Nucl. Part. Sci. **52**, (2002).
265. “Evidence for Oscillation of Atmospheric Neutrinos,” Super-Kamiokande Collaboration, Y. Fukuda *et al.*, Phys. Rev. Lett. **81**, 1562–1567 (1998). (I)

266. “ τ Neutrinos Favored Over Sterile Neutrinos in Atmospheric Muon Neutrino Oscillations,” Super-Kamiokande Collaboration, S. Fukuda *et al.*, Phys. Rev. Lett. **85**, 3999–4003 (2000). (I)
267. “Evidence for Neutrino Oscillations from the Observation of $\bar{\nu}_e$ Appearance in a $\bar{\nu}_\mu$ Beam,” LSND Collaboration, A. Aguilar *et al.*, Phys. Rev. D **64**, 112007 (2001). (I)
268. “The Status of MiniBooNE,” E. A. Hawker, Int. J. Mod. Phys. A **16 (S1B)**, 755–757 (2001). (I) For an up-to-date web page see: <http://www-boone.fnal.gov/> .

B. Cosmic microwave background radiation

The 2.7 K radiation left over from the Big Bang contains a wealth of information about both the early Universe and particle physics. In particular, the spatial pattern of its fluctuations indicates that the Universe is exactly on the border between open and closed, and strongly supports the idea that the Universe underwent a period of exponential inflation early in its history [134, 135, 269, 270, 271]. For a review of the cosmological parameters, see [272].

269. “Big-Bang Cosmology,” K. A. Olive and J. A. Peacock, in **Review of Particle Physics**, K. Hagiwara *et al.* [73], pp. 152–161. (I)
270. “Global Cosmological Parameters: H_0 , Ω_M , and Λ ,” M. Fukugita and C. J. Hogan, in **Review of Particle Physics**, K. Hagiwara *et al.* [73], pp. 166–172. (I)
271. “Cosmic Background Radiation,” G. F. Smoot and D. Scott, in **Review of Particle Physics**, K. Hagiwara *et al.* [73], pp. 177–181. (I)
272. “The Cosmic Triangle: Revealing the State of the Universe,” N. Bahcall, J. P. Ostriker, S. Perlmutter, and P. J. Steinhardt, Science **284**, 1481–1488 (1999). (I)

C. Baryon asymmetry of the Universe

To explain why the visible Universe seems to contain so many more baryons than antibaryons, Sakharov [273] proposed shortly after the discovery of CP violation that three ingredients were needed: (1) CP (and C) violation; (2) baryon number violation, and (3) a period in which the Universe is not in thermal equilibrium. All of these conditions are expected to be satisfied in a wide range of theories, such as grand unified theories (Sec. XI.E) in which quarks and leptons, and the electroweak and strong interactions, are unified with one another [274]. However, details of the mechanism are not clear [112, 113]. In some versions of the theory, for example, it is lepton number that is violated in the early stages of the Universe, giving rise to a lepton asymmetry that is then converted to a mixture of lepton and baryon asymmetry when the Universe has evolved further. For a recent review of this suggestion, see [275].

273. “Violation of CP Invariance, C Asymmetry, and Baryon Asymmetry of the Universe,” A. D. Sakharov, *Pis'ma Zh. Eksp. Teor. Fiz.* **5**, 32–35 (1967) [*JETP Lett.* **5**, 24–27 (1967)]. (I)
274. “Grand Unified Theories and the Origin of the Baryon Asymmetry,” E. W. Kolb and M. S. Turner, *Ann. Rev. Nucl. Part. Sci.* **33**, 645–696 (1983). (I)
275. “Neutrino Masses and the Baryon Asymmetry,” W. Buchmüller and M. Plumacher, *Int. J. Mod. Phys. A* **15**, 5047–5086 (2000). (I)

D. Dark matter

Only a small fraction of the matter in the Universe can be accounted for by baryons, leaving the remainder to consist of as-yet-unidentified matter or energy density [121]. Candidates for this *dark matter* are discussed in the *Review of Particle Physics* [276]. One class of candidates consists of the lightest supersymmetric particle (LSP), which may be stable; these suggestions are reviewed in [277].

276. “Dark Matter,” M. Srednicki and N. J. C. Spooner, in **Review of Particle Physics**, K. Hagiwara *et al.* [73], pp. 173–176. (I)
277. “Supersymmetric Dark Matter,” G. Jungman, M. Kamionkowski, and K. Griest, *Phys. Rep.* **267**, 195–373 (1996). (I)

E. Dark energy

The Universe appears not only to be expanding, but its expansion appears to be speeding up. Evidence for this behavior comes from the study of distant supernovae, which furnish “standard candles” for a cosmological distance scale [130, 272]. One interpretation is that a *cosmological constant* Λ (first proposed by Einstein shortly after he formulated the general theory of relativity) accounts for about 65% of the energy density of the Universe. This contribution is sometimes referred to as “dark energy,” to distinguish it from the “dark matter” accounting for nearly all of the remaining energy density aside from a few-percent contribution from baryons [269, 270]. An alternative suggestion is that the “dark energy” is due to a new field, dubbed “quintessence” [136]. For recent accounts of “dark energy” see [278] and [279].

278. “The Extravagant Universe,” R. P. Kirshner (Princeton University Press, 2002). (E)
279. “The Cosmological Constant and Dark Energy,” P. J. E. Peebles and B. Ratra, preprint astro-ph/0207347, to appear in *Rev. Mod. Phys.* (I)

XII. EXPERIMENTAL APPROACHES

The rise of the Standard Model would not have been possible without a variety of experimental facilities, including accelerators, detectors, and non-accelerator experiments. What follows is a brief description of some currently operating laboratories

and experiments. Fuller descriptions may be found through laboratory web sites, listed in Sec. VII.B, and through web sites of specific collaborations. Some references to recent experiments are given in this Section.

A. High energy accelerator facilities

1. Beijing Electron-Positron Collider (China)

This electron-positron collider with center-of-mass energy 2–5 GeV recently reported an improved measurement of R (see Sec. II.C) in this energy range [280]. It has made important contributions to the study of τ leptons, charmed particles, and $c\bar{c}$ bound states.

2. Brookhaven National Laboratory (U.S.A.)

The *Alternating-Gradient Synchrotron* (AGS) is a fixed-target proton accelerator with maximum energy of about 30 GeV. The first neutrino beam constructed at an accelerator was used at the AGS to show that the muon and electron neutrino are distinct from one another [281]. One of its most spectacular discoveries was the J/ψ particle, a bound state of a charmed quark and a charmed antiquark [185]. Recent experiments include the detection of the rare process $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ [282] and a precise measurement of the muon anomalous magnetic moment [283]. It serves as an injector to the *Relativistic Heavy-Ion Collider* (RHIC), whose maximum energy of about 200 GeV per nucleon permits studies of the quark-gluon plasma and other aspects of hadron physics at high densities.

3. CERN (Switzerland and France)

CERN’s 28-GeV Proton Synchrotron (PS) began operation in 1959. It served as a source of protons for the Intersecting Storage Rings (ISR), which began operation in the early 1970s and achieved a maximum center-of-mass energy of 62 GeV. Its protons were used to produce neutrinos which provided the first evidence for neutral currents in 1973 [177, 178]. The *Super-Proton-Synchrotron* (SPS), a 400-GeV fixed-target machine built in the mid-1970s, was converted to a proton-antiproton collider (the “ $S\bar{p}pS$ ”) early in the 1980s, leading to the discovery of the W and Z bosons in 1983 [284, 285]. The Large Electron-Positron (LEP) Collider [126] was commissioned in 1989, making a series of precise measurements at the center-of-mass energy of the Z boson (91.2 GeV) (an early measurement of the Z width pointed to three families of quarks and leptons [128]) before moving up in energy to nearly 210 GeV and ending its program in 2000 [286]. Its magnets have been removed, making way for the Large Hadron Collider (LHC), a proton-proton collider that will have a c.m. energy of 14 TeV [133, 287].

4. CLEO/CESR at Cornell (U.S.A.)

The Wilson Synchrotron at Cornell, a circular electron accelerator built in 1967, was converted in 1979 to an electron-positron collider, the Cornell Electron Storage Ring (CESR), with maximum energy 8 GeV per beam [288]. It arrived on the scene just in time to study the $\Upsilon(1S)$ $b\bar{b}$ resonance and its excited states, including the $\Upsilon(4S)$ which decays to a $B\bar{B}$ meson pair. Studies of B mesons have dominated the program of the CLEO detector at CESR until recently. For the next year or

two, CLEO will return to the $\Upsilon(1S, 2S, 3S)$ resonances, after which it is planned to optimize CESR to run at the lower energies appropriate for charm production [289]. This will permit a return to many interesting questions with a vastly improved detector and statistical sample.

5. DESY (Germany)

A circular electron accelerator at the Deutsches Elektronen Synchrotron (DESY) laboratory was converted to an electron-positron collider (DORIS) whose experimental program paralleled that of CESR/CLEO for a number of years, yielding important information about Υ spectroscopy and B mesons, for example through work of the ARGUS Collaboration. Subsequent machines included the larger e^+e^- collider PETRA (maximum c.m. energy 46 GeV) and the currently operating HERA lepton-proton collider, which has studied both e^-p and e^+p interactions. HERA has extended information on deep inelastic lepton scattering to new kinematic regimes and provided important information on the gluon structure of the proton.

6. Fermilab (U.S.A.)

The Fermi National Accelerator Laboratory in Batavia, Illinois, U.S.A., began operation in 1972 as a proton accelerator with initial energy 200 GeV, rising to 400 GeV within a year. With the addition of a ring of superconducting magnets in 1983 it was converted to an energy of 800 GeV capable of providing protons to fixed targets and proton-antiproton collisions with a center-of-mass energy of 1.8 TeV [127, 290]. Its energy has recently been upgraded to nearly 1 TeV per beam with the addition of a new 150-GeV proton ring called the Main Injector. Outstanding discoveries at Fermilab include those of the bottom quark in 1977 [188, 189], the top quark in 1994 [190, 191, 192, 193, 194, 195], and the tau neutrino in 2000 [291].

7. Frascati (Italy)

A major pioneer in the study of electron-positron collisions has been the Laboratori Nazionali di Frascati (INFN) near Rome, Italy. Starting in the early 1960s with the ADA collider and continuing through the ADONE storage ring, which began operation in the late 1960s, the laboratory has now begun to operate a machine called DAΦNE (DAFNE), which seeks to produce kaons and other particles through the reaction $e^+e^- \rightarrow \phi \rightarrow \dots$ at a center-of-mass energy of 1.02 GeV.

8. KEK (Japan)

In the early 1970s, a 12-GeV proton synchrotron was constructed in Japan near Tokyo at the National Laboratory for High Energy Physics, for which KEK (Ko-Energi-Kenkyujo) is the acronym in Japanese. The next major project at KEK, the TRISTAN e^+e^- collider, attained a center-of-mass energy in excess of 60 GeV, the highest in the world for such a machine at its debut in 1986. Among the topics studied by TRISTAN included weak-electromagnetic interference through the processes $e^+e^- \rightarrow (\gamma^*, Z^*) \rightarrow \dots$, where the asterisk denotes a virtual photon or Z . The latest project at KEK is the KEK-B e^+e^- collider, a lower-energy machine built in the TRISTAN tunnel, which is designed to produce pairs of B mesons with net motion on their center-of-mass by using unequal electron and positron energies. In this way the

positions at which the B mesons decay can be spread out longitudinally, permitting easier study of time-dependences that are of particular interest in CP-violating processes. The Belle detector operating at KEK-B [200] is producing significant results on B decays, as mentioned above [203]), as is the BaBar detector operating at PEP-II (see the description of SLAC, below).

9. Novosibirsk (Russia)

A series of e^+e^- colliders has operated at the Budker Institute for High Energy Physics in Novosibirsk for a number of years. Indeed, work at this laboratory helped to pioneer the study of beam dynamics essential for achieving such collisions. These colliders performed important measurements at the center-of-mass energies of the $\Upsilon(9.46)$ and $\phi(1.02)$ resonances, where the numbers denote the mass in GeV/c^2 .

10. Protvino (Russia)

The largest accelerator at present in Russia is a 76-GeV proton synchrotron at Serphukhov (Protvino), which began operation in the early 1970s. It was the first to detect rising meson-baryon cross sections [292], followed soon by the observation of a similar effect in proton-proton collisions at the CERN ISR (see above).

11. SLAC (U.S.A.)

The early program of the 30-GeV 2-mile-long linear electron accelerator at the Stanford Linear Accelerator Center (SLAC) included the discovery of pointlike constituents inside the proton through deep inelastic scattering [96, 152, 153]. In the early 1970s the SPEAR electron-positron storage ring was constructed with maximum center-of-mass energy equal to 7.4 GeV. Late in 1973 this machine confirmed a surprising enhancement of the e^+e^- annihilation cross section starting at a c.m. energy of 4 GeV seen earlier at the Cambridge Electron Accelerator (CEA), and in 1974 was one of two sources of the discovery of the J/ψ particle [186], the other being a fixed-target experiment at Brookhaven National Laboratory [185] (see above). In the mid-1970s construction was begun on PEP, an electron-positron collider with c.m. energy of about 30 GeV, which performed studies of the electroweak theory and was the first to measure the b quark lifetime. The energy of the LINAC was then raised to 50 GeV, both electrons and positrons were accelerated, and these were then bent in arcs to collide with one another at energies equal to or greater than the mass of the Z boson. This machine, the Stanford Linear Collider (SLC) [124], pioneered in precision studies of the Z boson through its Mark II and SLD detectors; its early measurement of the Z width was a piece of evidence for three families of quarks and leptons [128]. The latest SLAC project, the PEP-II asymmetric e^+e^- collider, has seen evidence for CP violation in B decays in its BaBar detector [199, 202] (see also KEK-B and Belle, above), and has achieved record luminosity for any collider. By the middle of this decade both BaBar and Belle expect to have produced and recorded several hundred million $B\bar{B}$ pairs.

12. Thomas Jefferson National Laboratory (U.S.A.)

A moderate-energy (5.7-GeV) electron accelerator, this machine studies interactions with nuclei and the photoproduction and electroproduction of resonances con-

taining light quarks (u, d, s), with an eye to seeing those that cannot be explained purely as $q\bar{q}$ mesons or qqq baryons. An upgrade to 12 GeV is under discussion.

280. “Measurements of the Cross Section for $e^+e^- \rightarrow$ hadrons at Center-of-Mass Energies from 2 GeV to 5 GeV,” BES Collaboration, J. Z. Bai *et al.*, Phys. Rev. Lett. **88**, 101802 (2002). (I)
281. “Observation of High-Energy Neutrino Reactions and the Existence of Two Kinds of Neutrinos,” G. Danby *et al.*, Phys. Rev. Lett. **9**, 36–44 (1962).
282. “Further Evidence for the Decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$,” BNL E787 Collaboration, S. Adler *et al.*, Phys. Rev. Lett. **88**, 041803 (2002). (I)
283. “Precise Measurement of the Positive Muon Anomalous Magnetic Moment,” BNL E821 Collaboration, H. N. Brown *et al.*, Phys. Rev. Lett. **86**, 2227–2231 (2001). (I) An updated version of this result has appeared recently with roughly half the experimental error: “Measurement of the Positive Muon Anomalous Magnetic Moment to 0.7 ppm,” BNL E821 Collaboration, G. W. Bennett *et al.*, Phys. Rev. Lett. **89**, 101804 (2002); **89**, 129903(E) (2002). See <http://phyppro1.phy.bnl.gov/g2muon/index.shtml> for latest details.
284. “Experimental Observation of the Intermediate Vector Bosons W^+ , W^- , and Z^0 ,” C. Rubbia, 1984 Nobel Lecture, available at <http://www.nobel.se/physics/laureates/1984/rubbia-lecture.html>. (I)
285. “Stochastic Cooling and the Accumulation of Antiprotons,” S. Van Der Meer, 1984 Nobel Lecture, available at <http://www.nobel.se/physics/laureates/1984/meer-lecture.html>. (I)
286. “Review of final LEP Results or a Tribute to LEP,” J. Drees, in **Proceedings of 20th International Symposium on Lepton and Photon Interactions at High Energies (Lepton Photon 01)** (Ref. [3]), pp. 349–373. (I)
287. “From LEP to LHC, a Review of Results and a Look to the Future,” L. Foà, Nucl. Phys. Proc. Suppl. **75A**, 28–36 (1999). (I)
288. “A Personal History of CESR and CLEO,” K. Berkelman, Cornell University report CLNS 02/1784 (unpublished). (I)
289. “CLEO-c and CESR-c: A New Frontier in Weak and Strong Interactions,” I. Shipsey, in Proceedings of 9th International Symposium on Heavy Flavor Physics, Pasadena, California, 10–13 Sept. 2001, AIP Conf. Proc. **618**, 427–437 (2002). (I)
290. “The First Large-Scale Application of Superconductivity: The Fermilab Energy Doubler, 1972–1983,” L. Hoddeson, Historical Studies in the Physical and Biological Sciences **18**, 25–54 (1987).

291. “Observation of ν_τ Interactions,” DONUT Collaboration, K. Kodama *et al.*, Phys. Lett. B **504**, 218–224 (2001). (I)
292. “Total Cross-Sections of π^+ , K^+ and p on Protons and Deuterons in the Momentum Range 15-GeV/ c to 60-GeV/ c ,” S. P. Denisov *et al.*, Phys. Lett. **36B**, 415–421 (1971). (I)

B. Non-accelerator experiments

1. Underground or underwater laboratories

The ability to perform experiments in a low-background environment is greatly increased by going deep underground, where cosmic ray interactions are less frequent. A number of major laboratories now are operating underground, including ones at the Kamioka mine (Japan) [293], Gran Sasso (Italy) [294], and Soudan (Minnesota, U.S.A.) [295]. Whereas the focus of several laboratories initially had been the search for proton decay, it has now broadened to include the study of interactions of neutrinos from atmospheric cosmic rays, the Sun, and even supernovae, and the search for effects of dark matter.

The next stage of operation of detectors in the laboratories mentioned above includes the study of artificially produced neutrinos. The Fermilab accelerator will send neutrinos to the MINOS detector [296] in Soudan. The proton synchrotron at KEK in the K2K experiment [293], and later a machine known as the Japan Hadron Facility [297], will direct neutrinos to the SuperKamiokande detector in Kamioka. Finally, a detector known as KamLAND [298], also in the Kamioka mine, will be sensitive to neutrinos from reactors over a large portion of Japan, and has already reported its first results [261].

Some current and forthcoming detectors will also be sensitive to naturally occurring neutrinos. These include the Sudbury Neutrino Observatory in Ontario [299], the Borexino experiment [300] in Gran Sasso, and the SuperKamiokande detector mentioned above. At the South Pole a number of phototubes have been sunk deep into the ice in the AMANDA experiment [301], which is envisioned in the IceCube experiment [302] to expand to an effective volume of a cubic kilometer. The RICE experiment [303] seeks to study the low-frequency tail (at several hundred MHz) of Čerenkov emission by electrons produced by neutrinos, also in South Polar ice. A number of neutrino detectors are also deployed or planned deep underwater, e.g., in Lake Baikal [304] and the Mediterranean Sea (ANTARES [305], NEMO [306], NESTOR [307]).

2. Atomic physics

A large accelerator is not always needed to study fundamental particle physics beyond the Standard Model. An example is the window on non-standard physics provided by atomic parity violation. (See the bibliography in [72].) Studies of weak-electromagnetic interference in atoms such as Cs, Tl, and Pb are in principle sensitive to new interactions and extended gauge theories, particularly if the effects of atomic physics can be separated from more fundamental effects.

3. Electric and magnetic dipole moments

The electric dipole moment of the neutron is an excellent probe of physics beyond the Standard Model, which predicts it to be orders of magnitude smaller than its current upper bound [243] of $|d_n| < 6 \times 10^{-26} e \cdot \text{cm}$. For a bibliography of experimental literature on electric dipole moments and atomic parity violation, see [72].

The magnetic dipole moments of particles also provide important constraints on the Standard Model. The anomalous magnetic moment of the muon, in particular, is sensitive to new-physics effects such as those that arise in some versions of supersymmetry [308]. The current status of measurements of this quantity indicates a possible deviation from standard-model predictions, but at a level which is not yet statistically compelling [283].

- 293. See the web page <http://www-sk.icrr.u-tokyo.ac.jp/>.
- 294. See the web page <http://www.lngs.infn.it/>.
- 295. See the web page <http://www.hep.umn.edu/soudan/>.
- 296. See the web page <http://www-numi.fnal.gov/>.
- 297. See the web page <http://jkj.tokai.jaeri.go.jp/>.
- 298. See the web page <http://www.awa.tohoku.ac.jp/html/KamLAND/>.
- 299. See the web page <http://www.sno.phy.queensu.ca/>.
- 300. See the web page <http://pupgg.princeton.edu/~borexino/>.
- 301. See the web page <http://amanda.berkeley.edu/amanda/>.
- 302. See the web page <http://icecube.wisc.edu/>.
- 303. See the web page <http://kuhep4.phsx.ukans.edu/~iceman/>.
- 304. See the web page <http://www-zeuthen.desy.de/baikal/>
or <http://thalia.ifh.de/baikal/>.
- 305. See the web page <http://antares.in2p3.fr/>.
- 306. See the web page <http://nemoweb.lns.infn.it/>.
- 307. See the web page <http://www.nestor.org.gr/>.
- 308. "The Muon Anomalous Magnetic Moment: A Harbinger for 'New Physics'," A. Czarnecki and W. J. Marciano, *Phys. Rev. D* **64**, 013104 (2001). (A)

C. Plans for future facilities

The particle physics community is developing a number of options to probe further beyond the Standard Model. These include a large linear e^+e^- collider, intense sources of neutrinos (“neutrino factories”), a muon collider, and a Very Large Hadron Collider (VLHC) with energy significantly greater than the LHC. Descriptions of all of these options may be found in the Proceedings of the 2001 Snowmass Workshop [309].

309. Proceedings of the APS / DPF / DPB Summer Study on the Future of Particle Physics (Snowmass 2001), Snowmass, Colorado, 30 June - 21 July 2001, eConf C010630 (2001).

XIII. SUMMARY

The Standard Model of electroweak and strong interactions has been in place for nearly thirty years, but precise tests have entered a phase that permits glimpses of physics beyond this impressive structure, most likely associated with the yet-to-be discovered Higgs boson and certainly associated with new scales for neutrino masses. Studies of CP violation in decays of neutral kaons or B mesons are attaining impressive accuracy as well, and could yield cracks in the Standard Model at any time. It is time to ask what lies behind the pattern of fermion masses and mixings. This is an *input* to the Standard Model, characterized by many free parameters all of which await explanation.

Many avenues exist for exploration beyond the Standard Model, both theoretical and experimental. A lively dialogue between the two approaches must be maintained, with adequate support for each, if we are to take the next step in this exciting adventure.

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