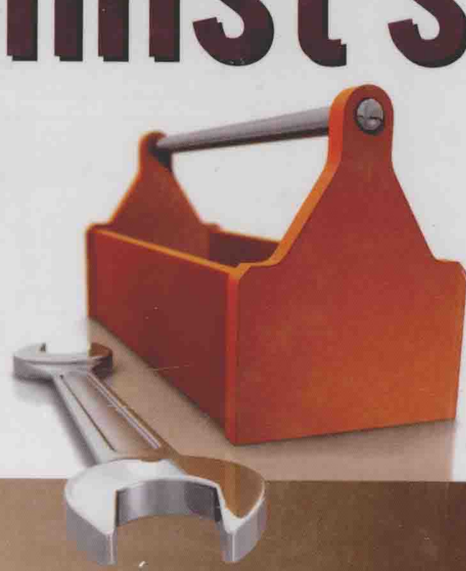
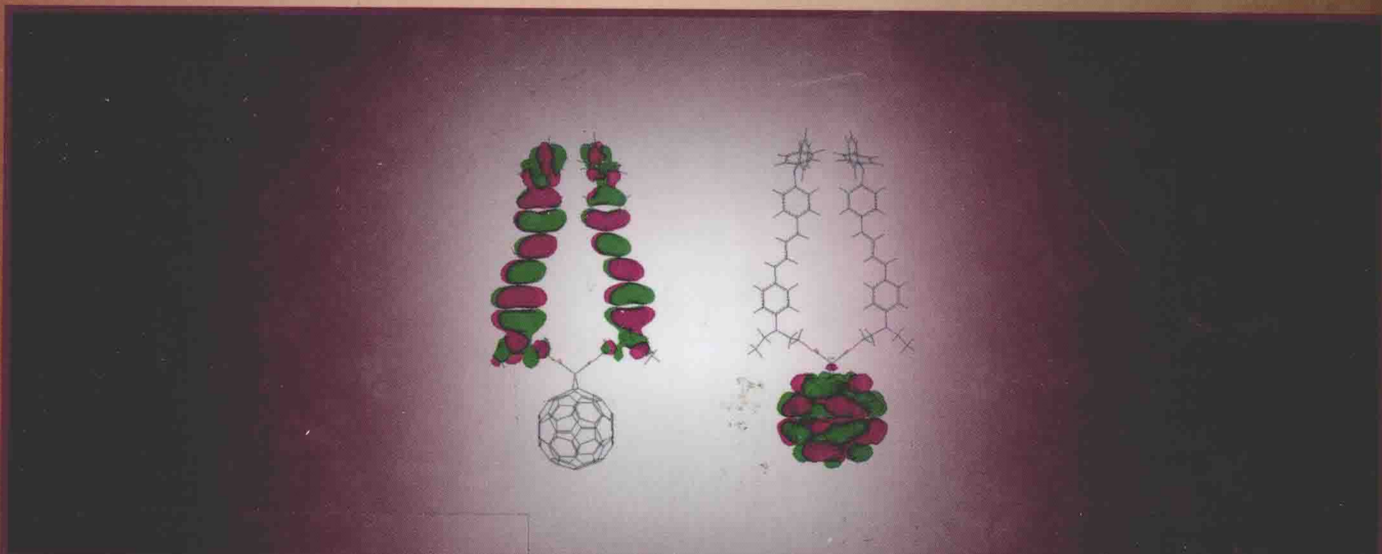
The Physical Chemist's TOOLBOX



ROBERT M. METZGER



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THE PHYSICAL CHEMIST'S TOOLBOX

Robert M. Metzger

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Foreword

In the first few years of the 21st Century it has become clear that an intrinsically cross-disciplinary perspective, in which expertise across the whole spectrum from condensed-matter physics through chemistry and materials science as well as molecular biology, will be necessary for successful research in almost any of these overlapping fields. However as more-and-more knowledge is accumulated and the complexity of that knowledge increases, researchers must bend over backward to avoid the ever-present tendency to over-specialize. This textbook aims to counter the pressure to over-specialize to which many doctoral programs are subject by offering a convergent ensemble perspective on the common elements that have developed.

The coverage is broad, including relevant concepts and equations from classical mechanics, electricity and magnetism, optics, special relativity, quantum mechanics, thermodynamics, statistical mechanics, kinetics, electrochemistry, crystallography, solid-state physics and electronics. The key formulas are presented succinctly, but with derivations and interspersed problems, so the student can easily assimilate and understand the intimate interconnections. Metzger has added two very useful chapters focused on instrumentation in order to introduce the readers quickly to a wide range of major research experimental approaches. He has included a detailed assessment of the types and value of the experimental information obtainable. Finally a bonus chapter has been included consisting of recent special topics. Interspersed throughout the text are occasional historical "sidelines", some amusing but always interesting and informative. These inserts, by occasionally breaking up the rhythm of general approach which is towards deeper understanding, help the learning process immeasurably by making it clear that the scientific advance is first-and-foremost a human endeavor driven by curiosity. Overall, the book is a tour de force.

The book offers a challenging and refreshing approach and it deserves to become a much used and dog-eared basic text, in fact a key reference on every book shelf, rather than a door-stop. It should become a basic text for the next generation of graduate students (post-graduate in UK parlance). Metzger's aim seems to be to lead students towards a much more broadly-based outlook than is the case at present, and it is to be hoped that professors will be inspired to lead them to this outlook. This is a revolutionary book, which does not aim to replace the more detailed traditional specialist courses in, say, quantum mechanics, statistical mechanics or solid-state physics. It just reveals a refreshing unity to the whole range of subjects in a very profound yet compact way.

SIR HAROLD WALTER KROTO, FRS
FLORIDA STATE UNIVERSITY

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CHAPTER 1

Introduction: A Physical Chemists 's Toolbox

"Indocti discant, amentque meminisse periti."
Charles Jean Hénault (1685–1770) in *Nouvel Abrégé Chronologique de l'Histoire de France jusqu'à la Mort de Louis XIV*

Jack Sherman: "Dr. Pauling, how does one get good ideas?"

Linus Pauling: "Well, I guess one must have many ideas, and throw away the bad ones."
Linus Carl Pauling (1901–1994)

"Never give in. Never give in. Never, never, never, never, never give in."
Sir Winston Churchill (1874–1965) at Harrow School, 29 October 1941

This compendium, "vademecum," or toolbox is an abbreviated introduction to, or review of, theory and experiment in physics and chemistry. The term "vade mecum" or "go with me" was the first tentative title for this book; it was associated with the learned and boring Baedeker® guidebooks for travel in the early 1900s: These Baedekers have been replaced with heavily illustrated and less boring Dorling–Kindersley® guides. Most students in 2011 who know some Latin would ask "vade mecum?" go with me? where? why?

The intended audience for this toolbox is the beginning researcher, who often has difficulty in reconciling recent or past classroom knowledge in the undergraduate or first-year graduate curriculum with the topics and research problems current in research laboratories in the twenty-first century. While several excellent and specialized monographs exist for all the topics

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discussed in this book, to my knowledge there is no single compact book that covers adequately the disparate techniques needed for scientific advances in the twenty-first century. In particular, there is a need to find "What will this or that technique do for my research problem?" The aim of this toolbox is thus fourfold:

1. Summarize the theory common to chemistry and physics (Chapters 2–6).
2. Introduce topics and techniques that lead to instrumentation (Chapters 7–9).
3. Discuss the advanced instrumentation available in research (Chapters 10 and 11).
4. Travel a path from crystals to nanoparticles to single molecules (Chapter 12).

The book is interspersed with problems to do: some trivial, some difficult. This expedient can keep the volume more compact, and it becomes a useful pedagogical tool. This book tries to be a mathematically deep, yet brief and useful compendium of several topics, which can and *should* be covered by more specialized books, courses, and review articles.

Throughout, the aim is to bring the novice up to speed. The teaching of chemistry leaned rather heavily toward mathematical and physical rigor in the 1960s, but this fervor was lost, as chemical, physical, and biochemical complexity eluded simple mathematical precision. Alas, chemical and biological phenomena are usually determined by small but significant differences between two very large quantities, whose accurate calculation is often difficult!

Lamentably, the recent educational trend has been to train what could be called one-dimensional scientists, very good in one subfield but blissfully unaware of the rest. It is sad that we no longer produce those broadly trained scientists of past generations, who were willing to delve into new problems far from their original interest: I am thinking of Hans Bethe, Peter Debye, Enrico Fermi, Linus Pauling, or Edward Teller. This toolbox tries to adhere to this older and broader tradition, redress the temporary malady, and help restore the universality of scientific inquiry.

To the instructor: This toolbox could form the basis of a one-year graduate course in physical chemistry and/or analytical chemistry, perhaps team-taught; it should be taught with mandatory problem sets (students will connect the dots by doing the suggested problems) and with recourse to traditional texts that cover, for example, quantum mechanics or statistical mechanics in much greater detail. I am reminded of the very successful one-year team-taught courses such as "Western Civilization" at Stanford University in the 1960s! I have taught the toolbox several times at the University of Alabama as a one-semester course, but found the pace exhausting.

To the many students who took my course: Thanks for being so patient.

To Chemistry and Physics departments: The toolbox could become a valuable resource for all entering graduate students, so maybe students, even in areas far from physical chemistry, should be encouraged to buy it and work at it on their own.

To the student: (1) Do the problems; (2) read around in specialized reference texts that may be suggested either in this toolbox or by your instructor(s); (3) discover whether the toolbox could be developed in new directions.

To myself: To adapt Tom Lehrer's (1928–) famous quip, I am embarrassed to realize that at my present age Mozart had been dead for 36 years.

Alan MacDiarmid (1927–2007) once said "Chemistry is about people": In this spirit, full names and birth and death dates are given to all the scientists quoted in this book; such brief historical data may help illuminate how and when science was done. I have resisted mentioning who was a Nobel prize winner: too many to list, and some worthy scientists—for example, Mendeleyeff, Eyring, Edison, Slater, and Tesla—were not honored. I owe a deep debt of gratitude to many people who have educated me over several decades, as live teachers and silent authors. In particular, I am indebted to Professor Willard Frank Libby (1908–1980), who taught us undergraduates at UCLA to love current research problems and led us into quite a few wild-goose chases; Professor Harden Marsden McConnell (1927–), who led us at Caltech and Stanford by example to see what are the interesting problems and what are "trivial" problems; Professor Linus Carl Pauling (1901–1994), who taught me electrical and magnetic susceptibilities with his incomparable photographic recall of data and dates, and with his insight and humanity about current events; Dr. Richard Edward Marsh (1922–) and Professor Paul Gravis Simpson (1937–1978), who taught me crystallography; Professor Michel Boudart (1925–), who introduced me to heterogeneous catalysis; Mr. William D. Good (1937–1978), who taught me combustion calorimetry; Professor Sukant Kishore Tripathy (1952–2000), who introduced me to Langmuir–Blodgett films; and finally, Professor Richard Phillips Feynman (1918–1983), who taught me about the Schwartzschild singularity and event horizons and who was a source of deep inspiration, pleasant conversations, and mischievous fun. Thanks are also due to two persons who helped me greatly in my academic career and taught me a thing or two about what good science really means: Professor Andrew Peter Stefani (1927–) of the University of Mississippi and Professor Michael Patrick Cava (1926–2010) of the University of Alabama. Professor Carolyn J. Cassady (University of Alabama) kindly allowed me to use an experiment she had devised for students of mass spectrometry.

The following books have inspired me: (1) *Principles of Modern Physics* by Robert B. Leighton, (2) *Theoretical Physics* by Georg Joos, (3) *The Feynman Lectures on Physics* by Richard P. Feynman, and (4) *Principles of Instrumental Analysis* by Doug Skoog, James Holler, and Stanley Crouch. In this twenty-first century, much help was obtained on-line from Wikipedia, but "*caveat emptor*"!

Writing is teaching but also learning; Marcus Porcius Cato (234–149 BC), who was echoing Solon (630–560 BC), said "I dare to say again: '*senesco discens plurima.*'"

Thanks are due to several friends and colleagues, who corrected errors and oversights in the early drafts: Professor Massimo Carbucicchio (University of Parma, Italy), Professor Michael Bowman, Dan Goebbert, Shanlin Pan, and Richard Tipping (University of Alabama), Professor Harris J. Silverstone (Johns Hopkins University), Professor Zoltán G. Soos (Princeton University), Dr. Ralph H. Young (Eastman Kodak Co.), and Adam Csoeke-Peck (Brentwood, California). The errors that remain are all mine; *errare humanum est, sed perseverare diabolicum* [Lucius Anneus Seneca (ca. 4 BC–AD 66)]. To the reader who finds errors, my apologies: I will try to correct the errors for the next edition; echoing what Akira Kurosawa (1910–1998) said in 1989, when he received an honorary Oscar for lifetime achievements in cinematography: "So sorry, [I] hope to do better next time."

CHAPTER 2

Particles, Forces, and Mathematical Methods

"Viribus Unitis"
[with united forces]
Emperor Franz Josef the First (and the Last) (1830–1916)

"It is difficult to make predictions, especially about the future."
Yogi Berra (1925–)

This chapter summarizes the fundamental forces in nature, reviews some mathematical methods, and discusses electricity, magnetism, special relativity, optics, and statistics.

Sideline. The name "physics" derives from the Greek word $\phi\upsilon\sigma\iota\varsigma$ (= nature, essence): Early physicists like Newton were called natural philosophers. The word "chemistry," through its Arabic precursor alchimya, derives from the Greek word $\chi\eta\mu\iota$ (= black earth), a tribute to the Egyptians' embalming arts. Mathematics comes from the Greek $\mu\alpha\theta\eta\mu\alpha$ (= learning, study). Algebra comes from the Arabic "al-jabr" (= transposition [to the other side of an equation]). Calculus (as in "infinitesimal calculus") is the Latin word for a small pebble.

2.1 FUNDAMENTAL FORCES, ELEMENTARY PARTICLES, NUCLEI AND ATOMS

The four **fundamental forces**, their governing equations, the mediating particles, their relative magnitudes, and their ranges are listed in Table 2.1.

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Table 2.1 The Fundamental Forces

Force	Law	Equation	Mediating Particle	Relative Magnitude	Range
Gravitation	Newton's law	$\mathbf{F}_{12} = -Gm_1M_2\mathbf{r}_{12}/r_{12}3$	Graviton (?)	10^{-39}	Infinite
Electricity	Coulomb's law	$\mathbf{F}_{12} = q_1\, q_2\, \mathbf{r}_{12}/4\,\pi\,\varepsilon_0\, r_{12}3$	Photon	10^{-2}	Infinite
Weak nuclear	—	—	Vector boson	10^{-5}	10^{-18} m
Strong nuclear	Inter-quark	—	Gluon[a]	1	10^{-15} m
Strong nuclear	Inter-nucleon	—	Pion (gluon?)[a]	1	10^{-15} m

Source: Adapted from Serway [1].

[a] For nucleon–nucleon strong interactions within nuclei, pions (= two-quark particles; see below) may be the mediating particles: Gluons are probably not involved directly, since the nucleons have no "color charge." The inter-nucleon potential goes to zero beyond $1.7\,\text{fm} = 1.7 \times 10^{-15}\,\text{m}$.

The first (and weakest) force is Newton's[1] force of universal gravitation (1687) [2]:

$$\mathbf{F}_{12} = -Gm_1M_2\mathbf{r}_{12}/r_{12^3} \tag{2.1.1}$$

which describes the attractive force $\mathbf{F}_{12}$ between two bodies of masses m_1 and M_2 placed a distance $\mathbf{r}_{12}$ apart, where G is the **constant of gravitation**. The largest visible objects in the universe (galaxies, stars, quasars, planets, satellites, comets) are held together by this weakest force, which may be transmitted by a presumed but hitherto unobserved mediating particle called the **graviton**. Its range extends to the whole universe. Masses are always positive.

The second force is the electrical force, which obeys Coulomb's[2] law (1785) [3]:

$$\mathbf{F}_{12} = q_1\, q_2\, \mathbf{r}^{12}/4\,\pi\,\varepsilon_0\, r_{12^3} \tag{2.1.2}$$

which describes the attractive (or repulsive) force $\mathbf{F}_{12}$ between two electrical charges q_1 and q_2 (positive or negative) placed $\mathbf{r}_{12}$ apart, where ε_0 is the electrical permittivity of vacuum. The fundamental electrical monopole (electron) is probably infinitely stable; the mediating particle for the electrical force (**photon**) is observed and well understood. Magnetism is usually due to moving electrical charges, but its monopole has never been seen, so magnetism is not really an independent force; atoms have magnetic properties, and in wires the gegenions of electrical currents are "stationary," yet the overall charge is zero: Hence magnetism is a special relativistic effect. As explained below, electricity and magnetism are well described by Maxwell's[3] four field equations [4].

The third force is the "weak nuclear" or "Fermi"[4] force (1934), which stabilizes many radioactive particles and the free neutron; it explains "beta decay" and positron emission (e.g., the free neutron decays within a half-life of 13 minutes into a proton, an electron, and an electron antineutrino). The weak force has a very narrow range.

[1] Sir Isaac Newton (1642–1727).

[2] Charles-Augustin de Coulomb (1736–1806).

[3] James Clerk Maxwell (1831–1879).

[4] Enrico Fermi (1901–1954).

The fourth and strongest force in the universe is the "strong nuclear force," which binds together the nuclei and the constituents of atomic nuclei, but has an extremely narrow range. Indirect experimental evidence exists for a mediating particle (gluon). Nucleons (neutrons, protons) and maybe nuclei consist of "elementary" particles called **quarks**, which have never been seen free, although proton–proton scattering experiments show that protons consist of "lumps," which may be the best experimental evidence for quarks.

Between 1900 and 1960 a zoo of 100-odd stable and unstable elementary particles were discovered; the shortest-lived among them were called "resonances"; quarks were proposed in 1964 by Zweig[5] and Gell-Mann[6] to help order this zoo. Within the nucleus, the inter-nucleon "strong" force was traditionally thought of as being mediated by pions (themselves combinations of two quarks). The nuclear "shell model" assigns quantum numbers to the protons and neutrons that have merged to form a certain nucleon. Certain "magic values" of these nuclear quantum numbers explain why certain nuclei are more stable (have longer lives) than others.

Sideline. The name "quark" comes from a sentence in Joyce's[7] *Finnegan Wake*; a free quark has never been isolated, but physicists have not looked in German grocery stores, where Quark is a well-known special soft cheese!

In 1960 electrical and weak forces were merged by Glashow[8] into **electroweak theory**. Evolving in the 1960s and 1970s from the quark hypothesis, the **Standard Model** of Glashow, Weinberg[9], and Salam[10] explains nucleons and other particles (hadrons, baryons, and mesons) as unions of either three or two "quarks" each, with a new set of *ad hoc* "quantum numbers." This Standard Model has a symmetry basis in the finite special unitary group SU(3), along with a mathematical expression in **quantum chromodynamics**, but does not yield a force field. These seemingly provisional *ex post facto* arguments and quantum numbers are reminiscent of the chemical arguments used by Mendeleyeff[11] in 1869 to construct the Periodic Table of chemical elements (whose explanation had to wait for quantum mechanics in the 1920s).

Sideline. Mendeleyeff divorced his wife in 1882 and married a student: By the rules of the Russian Orthodox Church, he became a bigamist, and according to an Edict of the Russian Czar, only members of the Church in good standing could teach in Russian Universities. When apprised of the dilemma, Czar Alexander III[12] said: "Mendeleyeff may have two wives, but I only have one Mendeleyeff": Professor. Mendeleyeff kept his job!

Table 2.2 lists the presently known **fundamental particles** (unobserved quarks and some neutrinos), the **elementary particles**, and the observed

[5] George Zweig (1937–).

[6] Murray Gell-Mann (1929–).

[7] James Augustine Aloysius Joyce (1842–1941).

[8] Sheldon Glashow (1932–).

[9] Steven Weinberg (1933–).

[10] Mohammed Abdus Salam (1926–1996).

[11] Dmitri Ivanovich Mendeleyeff (1834–1907).

[12] Alexander III Alexandrovich Romanov, Czar of All the Russias (1845–1894).

Table 2.2 Fundamental (Quark, Gluon, Graviton, Neutrino) and Elementary (= Fundamental Plus 2-Quark and 3-Quark Combinations) Particles[a]

Particle Name	Symbol	Lifetime (τ/s)	Relative Mass m'	Relative Electron Charge Q	Spin S	Parity P	Isospin T
Quarks [fundamental (with six "flavors" u, d, s, c, b, and t) but so far unobserved as single particles]							
Up Quark	u	∞?	~4.6	+2/3	1/2	+1	1/2
Anti-up*	$\bar{u}$	∞?	~4.6	−2/3	1/2	−1	1/2
Down Quark	d	∞?	~16	−1/3	1/2	+1	1/2
Anti-down*	$\bar{d}$	∞?	~16	1/3	1/2	−1	1/2
Charmed Quark	c	∞?	~2490	+2/3	1/2	+1	0
Anti-charmed*	$\bar{c}$	∞?	~2490	−2/3	1/2	−1	0
Strange Quark	s	∞?	~200	−1/3	1/2	+1	0
Anti-strange*	$\bar{s}$	∞?	~200	1/3	1/2	−1	0
Bottom Quark	b	∞?	~8480	−1/3	1/2	+1	0
Anti-bottom*	$\bar{b}\bar{b}$	∞?	~8480	1/3	1/2	−1	0
Top Quark	t	∞?	>3.4E5	2/3	1/2	+1	0
Anti-top*	$\bar{t}$	∞?	>3.4E5	−2/3	1/2	−1	0
Fundamental interaction carriers (for gluons, combination of color and anti-color)							
Photon	ν	∞	0	0	1	−1	1,0
Vector boson	W^+	?	1.6E5		1	—	1
Vector boson	Z	?	1.8E5	1	1	—	1
Vector boson	W^-	?	1.6E5	1	1	—	1
Gluon1	$r\bar{y}$	?	0	0	1	—	0
Gluon2	$r\bar{b}$	?	0	0	1	—	0
Gluon3	$y\bar{r}$	?	0	0	1	—	0
Gluon4	$y\bar{b}$	?	0	0	1	—	0
Gluon5	$b\bar{r}$	?	0	0	1	—	0
Gluon6	$b\bar{y}$	?	0	0	1	—	0
Gluon7	$(r\bar{r} - y\bar{y})2^{-1/2}$	?	0	0	1	—	0
Gluon8	$(r\bar{r} + y\bar{y} - b\bar{b})6^{-1/2}$	?	0	0	1	—	0
Electron neutrino	ν_e	∞	0	0	1/2	—	—
Electron antineutrino*	$\bar{\nu}_e$	∞	0	0	1/2	—	—
Muon neutrino	ν_μ	∞	0	0	1/2	—	—
Muon antineutrino*	$\bar{-}\nu\mu$	∞	0	0	1/2	—	—
Tau neutrino	ν_T	∞	0	0	1/2	—	—
Tau antineutrino*	$\bar{-}\nu_T$	∞	0	0	1/2	—	—
Graviton?	G	0?	0	0	2	—	—
Higgs boson?	H^0	?	>224	0	0	—	—
Leptons (elementary particles)							
Electron	e	∞	1	−1	1/2	—	—
Positron*	e^+	∞	1	+1	1/2	—	—
Muon‡	μ^-	2.2E-6	237	−1	1/2	—	—
Positive muon*	μ^+	—	237	+1	1/2	—	—
Tau	τ^-	<4E-13	3477	−1	1/2	—	—
Positive tau*	τ^+	—	3477	+1	1/2	—	—
Mesons (combinations of two quarks)							
Positive pion	π^+	2.6E-8	273	1	0	−1	1
Negative pion*	π^-	3E-8	273	−1	0	−1	1
Neutral pion	π^0	8E-17	264	0	0	−1	1

z-cmp Isospin T_z	Baryon# *Ba*	Strangeness *St*	Charm *Ch*	Beauty *By*	Truth *Tr*	Quark Composition
+1/2	1/3	0	0	0	0	u
+1/2	−1/3	0	0	0	0	$\bar{u}$
−1/2	1/3	0	0	0	0	d
−1/2	−1/3	0	0	0	0	$\bar{d}$
0	1/3	0	+1	0	0	c
0	−1/3	0	−1	0	0	$\bar{c}$
0	1/3	−1	0	0	0	s
0	−1/3	+1	0	0	0	$\bar{s}$
0	1/3	0	+1	0	0	b
0	−1/3	0	−1	0	0	$\bar{b}$
0	1/3	0	0	0	+1	t
0	−1/3	0	0	0	−1	$\bar{t}$
—	0	0	—	—	—	
1	—	—	—	—	—	
0	—	—	—	—	—	
−1	—	—	—	—	—	
0	0	—	—	—	—	
0	0	—	—	—	—	
0	0	—	—	—	—	
0	0	—	—	—	—	
0	0	—	—	—	—	
0	0	—	—	—	—	
0	0	—	—	—	—	
0	0	—	—	—	—	
—	0	—	—	—	—	
—	0	—	—	—	—	
—	0	—	—	—	—	
—	0	—	—	—	—	
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—	0	—	—	—	—	
—	0	—	—	—	—	
—	0	—	—	—	—	
—	0	—	—	—	—	
—	0	—	—	—	—	
—	0	—	—	—	—	
+1	0	0	—	—	—	$u\bar{d}$
−1	0	0	—	—	—	$\bar{u}d$
0	0	0	—	—	—	$(u\bar{u} - d\bar{d})/\sqrt{2}$

(*continued*)

Table 2.2 ***(Continued)***

Particle Name	Symbol	Lifetime (τ/s)	Relative Mass m'	Relative Electron Charge Q	Spin S	Parity P	Isospin T
Neutral ρ meson	ρ^0	5E-24	1510	1	−1	−1	0
Positive kaon	K^+	1.2E-8	493.8	1	0	−1	1/2
Negative kaon*	K^-	1.2E-8	493.8	−1	0	−1	1/2
Neutral kaon	K^0	8.9E-8	493.8	0	0	−1	1/2
Neutral kaon*	$\bar{K}^0$	5.2E-8	493.8	0	0	−1	1/2
η meson	η^0	5E-19	549	0	−1	−1	0
η' meson	η'	3E-21	958	0	−1	−1	0
Hadrons or Baryons (combinations of three quarks)							
Proton	p	∞	1838	+1	1/2	+1	1/2
Anti-proton*	p^-	???	1838	−1	1/2	+1	1/2
Neutron	n	886	1839	0	1/2	+1	+1/2
Lambda^0	Λ^0	2.6E-10	1116	0	1/2	+1	0
Charmed lambda$^+$	Λ^{c+}	2.0E-13	1116	1	1/2	+1	0
Bottom lambda$^-$	Λ^{b0}	1.4E-12	5622	0	1/2	+1	0
Sigma$^+$	Σ^+	8E-11	1189	1	1/2	+1	1
Sigma^0	Σ^0	6E-20	1192	0	1/2	+1	1
Sigma$^-$	Σ^-	1.5E-10	1197	−1	1/2	+1	1
Charmed sigma^{++}	Σ^{++}	3.0E-22	1200	2		+1	1
Xi^0	Ξ^0	2.9E-10	1315	0	1/2	+1	+1/2
Xi$^-$	Ξ^-	1.6E-10	1321	−1	1/2	+1	+1/2
Omega$^-$	Ω^-	1.6E-10	1672	−1	3/2	+1	0

[a] The masses m' are rest masses, quoted relative to the mass of the electron, $m_e = 9.1093897 \times 10^{-31}$ kg, whose rest mass energy is 0.51099906 MeV c^{-2}; the charges Q are quoted relative to the absolute value of the charge on the electron, $e = 1.609 \times 10^{-19}$ C; lifetime is given as the known half-life (s) in the abbreviated format 2.34E-3, which translates as $\tau = 2.34 \times 10^{-3}$ s; the lifetime is given as infinite for those particles which have infinite lifetimes (except in particle–antiparticle collisions). "Quark composition." gives the composition of the elementary particle in terms of its presumed quark components. Not all unstable hadrons or mesons are listed. Antiparticles to other listed particles are indicated by asterisks (*), but not all antiparticles are listed. The quantum numbers are for relative charge (Q), spin (S), parity (P), isospin (T), z-component of isospin (T_z), baryon number (Ba), Strangeness (St), Charm (Ch), Beauty or bottomness (By), and Truth or topness (Tr) [1]. The amended Gell–Mann–Nishijima [Kazuhiko Nishijima (1926–2009)] relation is $Q = T_z + (Ba + St + Ch + By + Tr)/2$.
[b] The muons were first called mu mesons, but are now better known as muons, leaving the π mesons, or pions, as the particles which may carry the inter-nucleon strong force.

(photon, vector bosons) and unobserved (gluons, gravitons, Higgs[13] bosons) particles that mediate the interactions (strong, electromagnetic, weak, and gravitational) between them. Here "fundamental" is used for the presumed building blocks, while "elementary" is used for the experimentally observed smallest constituents of matter.

The **lifetimes** t, or **half-lives** τ can measured directly when $\tau \geq 1.0\times 10^{-12}$ s or so (τ is defined as the time elapsed from the initial formation of a number N of these particles to the time when their population has decreased to $N/2$). Shorter half-lives ($\tau < 1.0 \times 10^{-12}$ s) are inferred from a measured "natural" or Breit[14]–Wigner[15] or Lorentzian[16] linewidth ΔE of

[13] Peter Higgs (1929–).

[14] Gregory Breit (1899–1981).

[15] Eugene Paul Wigner (1902–1995).

[16] Hendrik Antoon Lorentz (1853–1928).

z-cmp Isospin T_z	Baryon# *Ba*	Strangeness *St*	Charm *Ch*	Beauty *By*	Truth *Tr*	Quark Composition
0	—	—	—	—	—	$(u\bar{u} + d\bar{d})/\sqrt{2}$
1/2	—	1	—	—	—	$u\bar{s}$
−1/2	—	−1	—	—	—	$\bar{u}s$
−1/2	—	1	—	—	—	$d\bar{s}$
1/2	—	−1	—	—	—	$\bar{d}s$
0	—	0	—	—		$(u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}$
0	—	0	—	—		$(u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$
+1/2	+1	0	—		—	$u\bar{u}d$
+1/2	−1	0	—		—	$u\bar{u}\bar{d}$
−1/2	+1	0	—		—	$ud\bar{d}$
0	+1	−1	0		—	uds
0	+1	0	1	0	0	udc
0	−1	0	0	1	0	udb
1	+1	−1	0	0	0	uus
0	+1	−1	0	0	0	uds
−1	+1	−1	0	0	0	dds
−1	+1	−1	1	0	0	uuc
+1/2	+1	−2	—		—	
−1/2	+1	−2	—		—	
0	+1	−3	—		—	sss

their energy E and the Heisenberg[17] uncertainty principle condition (discussed further in Section 3.1) $\Delta E\,\Delta\tau \geq (h/4\pi \equiv \eta/2)$, where $\hbar$ is Planck's[18] constant of action (one can argue whether τ is a lifetime or a half-life in the Heisenberg sense). In practice, one estimates the half-life τ from the width of the resonance ΔE_{12} (= width at half-maximum height; see Fig. 2.1)

$$\tau \equiv \hbar/2\,\Delta E_{12} \qquad (2.1.3)$$

Searches for individual quarks using high-energy accelerators have failed, up to rest-mass energies in vast excess of the masses of the stable known leptons and hadrons. Searches for quarks in minerals and seawater,

[17] Werner Heisenberg (1901–1976).

[18] Max Planck (1858–1947).

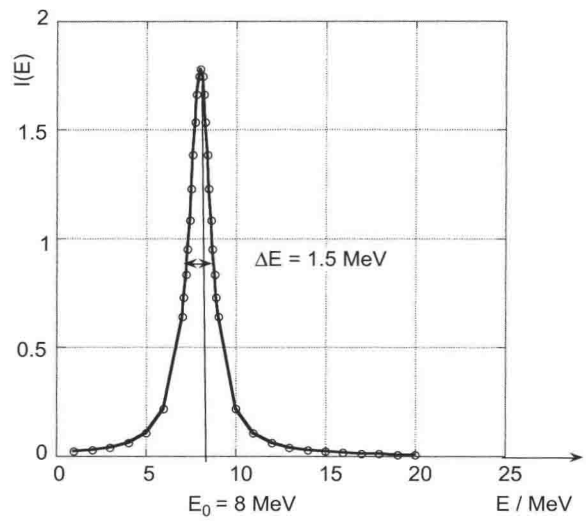

FIGURE 2.1
Natural or Breit–Wigner or Lorentzian linewidth $I(E) = \left[(E - E_0)^2 + \Delta E^2/4\right]^{-1}$ for $\Delta E = 1.5$ MeV at half-maximum centered around $E_0 = 8.0$ MeV.

potentially left over when hadrons and leptons first formed, and focused on their putative fractional electrical charge, have also failed. Therefore an explanation of "quark confinement" has emerged: Quarks are confined by twos and threes in a very deep potential well (Fig. 2.2), and are held together by forces so strong that only maybe future high-energy accelerator experiments may (if ever) detect an individual quark. The sum of the probable rest masses of one u, one $\bar{u}$, and one d quark, namely $4.6 + 4.6 + 16 = \sim 25.2\, m_e$ is far short of the rest mass of the proton (1836 m_e).

Efforts to unify all four forces into a **single grand unified theory** have failed. The very elegant **string theory** has provided no measurable predictions.

The rest masses of the particles cannot yet be predicted; the proposed **Higgs boson**, which has not yet been detected, may explain why particles have mass. Experimental searches are ongoing for free quarks, gluons, and the Higgs boson. After 15 years of construction, in March 2010 the 27-km radius Large Hadron Collider at the Centre Européen de Recherches Nucléaires near Geneva, Switzerland has reached an energy of 7 TeV (1.12 μJ per particle), so there is some hope for future discoveries.

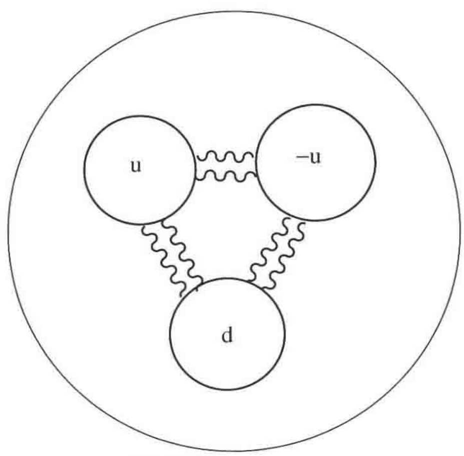

FIGURE 2.2
This crude model tries to show the confinement of three quarks ["up" (u), "conjugate up" ($\bar{u}$), and "down" (d), with electrical charges +2/3, +2/3, and −1/3] inside a proton. The springs depict the mutual interactions, meditated by virtual gluons, which are (somehow) limited by the inter-quark potential to remain within the inside of the proton.