SMALL STUFF

From Democritos through the Alchemists of the Middle Ages and Mendeleyev's Periodic Table of the Elements all the way to modern ELEMENTARY PARTICLE PHYSICS, one of the first duties of "Natural Philosophers" has been to make up *lists* of all possible *constituents of matter* — preferably (for the sake of simplicity) including only the *irreducible* components.

This notion may well be obsolete in the literal physical sense, but the concept lives on; and it is tempting (if misleading) to describe Elementary Particle Physics as the art of inventing the simplest possible *classification scheme* for the "zoo" of known "elementary" particles.

Objects or entities can only be *classified* in terms of their *properties*. Thus the first task is to *define* all the (known) intrinsic properties of matter as concisely as possible, invent ways of *measuring* how much of each property a given particle has, and do the experiments. Of course, this is a highly *iterative* process — after each round of experiments the theorists have to go back to their drawing boards and revise the Ultimate Classification Scheme — but the idea is still the same. My task is now to summarize in one Chapter over half a century of progress along these lines. Naturally I will omit as many of the false starts and backtracks as possible, to make it look as if the present scheme[1] is correct and was obvious from the outset.

26.1 High Energy Physics

Before we begin to construct a classification scheme for the "elementary" particles, we need to have some feeling for the phenomenology involved — and maybe even a bit of historical perspective.

In some sense HIGH ENERGY PHYSICS (the experimental discipline) began when the first cyclotron capable of producing *pions* "artificially" was built by Ernest Orlando Lawrence at Berkeley in the early 1940's.[2] However, *high energy physics* (the behaviour of Nature) began in the instant of creation of the Universe — and it will be a long time before we are able to study the interactions of matter at the energies and densities of those first few femtoseconds.[3] I will compromise by dating HIGH ENERGY PHYSICS (the modern human endeavour) from the hypothesis of Hideki Yukawa in 1935 that the STRONG nuclear force must be mediated by the exchange of particles of intermediate [between electrons and protons] mass, which he therefore named "MESONS" [as in *meso*zoic or *Meso*potamia(?)]. Where did he ever get such an idea?

26.1.1 $\mathcal{QED}$

It began with the FEYNMAN DIAGRAM first shown in the Chapter on RELATIVISTIC KINEMATICS. In Fig. 26.1 I show the Feynman diagrams for single and double photon exchange in QUANTUM ELECTRODYNAMICS or $\mathcal{QED}$, for which Richard P. Feynman shared a Nobel Prize. As before, I will draw Feynman diagrams "left to right" instead of the

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[1] Actually, to be honest, this is not the present scheme. It is the one I learned 30 years ago, beefed up with the tidbits I have absorbed since then. Nowadays people talk about the "*Standard Model*," a more elegant presentation of the dog's breakfast you will get from this Chapter — but not, I think, really a different story. Some of the lower limits on the masses of as yet undiscovered particles will have doubled or tripled recently, so don't take the *numbers* in the tables too seriously.

[2] Lawrence's 184 inch Cyclotron, the biggest *solid pole-tip magnet* synchrocyclotron ever built, was originally conceived as a giant *mass spectrometer* for separating the isotopes of uranium for the first fission bomb; however, a far more efficient method was invented soon after it was built, and "the 184" went into service as a pion and muon producer. Many Ph.D. theses (including my own in 1972) were written on experiments performed at the 184 until it was dismantled in the 1980's to make room for what was then the world's most intense Synchrotron Light Source on the same site at what has been called the Lawrence Berkeley Laboratory (LBL) since the end of the 1960's. [Before that it was called the Lawrence Radiation Laboratory (LRL); the name was changed to avoid association with the other LRL branch in Livermore (now known as LLL, the Lawrence Livermore Laboratory) where weapons research is conducted, and to expunge that fearsome word "Radiation." Spineless politicians!]

[3] I refer, of course, to the "BIG BANG" scenario, which is almost universally regarded as the best model of cosmogony [a fancy word for Creation]. Perhaps I will get to say a few words about the Big Bang in a Chapter on GENERAL RELATIVITY.

conventional "down to up." The idea of $\mathcal{QED}$ was (and is) that *all* electromagnetic interactions between charged particles can be described in terms of the *exchange of photons* created by one particle and destroyed by another. The simplest case is the "first-order" diagram in Fig. 26.1, where two electrons exchange a *single* photon. The next (second-order) process is a factor of α^2 less important, where $\alpha \approx \frac{1}{137}$ is the FINE STRUCTURE CONSTANT (not a very mnemonic name any more), which is (sort of) the *strength* of the $\mathcal{QED}$ "vertex" (the point where the photon begins or ends). Because each successive diagram (single photon exchange, double photon exchange, triple photon exchange, *etc.*) is a factor of about 19,000 less important than the one before, $\mathcal{QED}$ is a PERTURBATION THEORY that *converges very rapidly.* That is, you can get a pretty accurate result with very few diagrams.

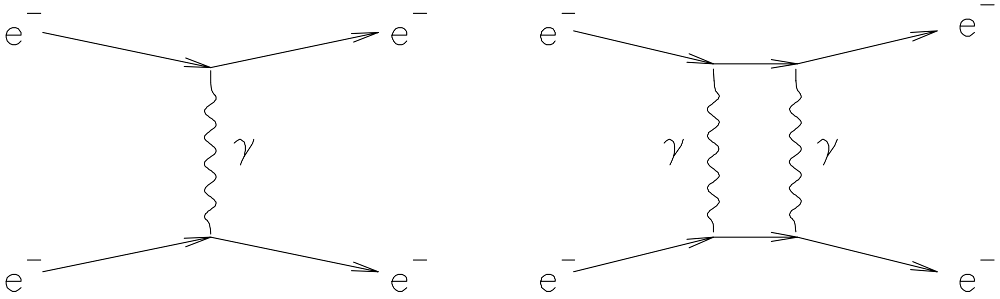

Figure 26.1 FEYNMAN DIAGRAMS for electromagnetic electron-electron scattering in first order (left) and second order (right).

Each diagram, you see, is *rigourously equivalent* to a big messy integral which is definitely less appealing to the Right Hemisphere; but the big integral can be evaluated to give the correct formula for the interaction of the two electrons *to that order in* $\mathcal{QED}$, properly taking into account all the ramifications of QUANTUM FIELD THEORY. Which is. . . ? Let's take another step back for better perspective.

26.1.2 Plato's Particles

When Quantum Mechanics was first developed, it was formulated in a *nonrelativistic limit* — *i.e.*, the particles involved were presumed not to have enough kinetic energy to create *other* particles. Because, if they did, then not only the quantum states of each particle, but *the number of particles present*, would have to be described by the theory. You can see that the combination of Quantum Mechanics with Relativity makes RELATIVISTIC QUANTUM MECHANICS a rather more complicated sort of problem.

Quantum mechanical equations were found for bosons (the KLEIN-GORDON EQUATION) and for fermions (the DIRAC EQUATION) which obeyed the correct relativistic transformations, but now the WAVE FUNCTIONS [ϕ for bosons, ψ for fermions] could not be interpreted as simply as before — in terms of the probability amplitude for a *single particle.* Now they had to be interpreted as the probability amplitude of the FIELD of the corresponding particle, for which the *number of such particles* was merely a quantum number of the field.[4]

As a result, when a Particle Physicist speaks of "THE ELECTRON," (s)he is referring to the electron FIELD, an absolutely literal example of the Platonic Ideal, in which the disposition (and even the *number*) of actual individual electrons is merely a *state* of THE ELECTRON [field]. An actual *single* individual particle in the laboratory is rarely the source of much information about the complete set of all its identical siblings.

A given Feynman diagram therefore represents *one possible case* of the numbers and types of particles present in an interaction with a specified initial and final state. It is one possible *manifestation* of the FIELDS.

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[4] Just to give a hint of how this works, ψ is now composed of some complex exponential wave functions multiplied by *creation* and *annihilation operators* that respectively increase and decrease the number of particles of that species by one. The creation and annihilation operators obey an algebra that corresponds to the statistical properties of the particle — *e.g.*, for fermions no two can be in the same state, *etc.* I will resist the temptation to show any of the equations, which are actually very compact but (as one might expect) have an extremely high "interpretation density."

26.1.3 The Go-Betweens

A common feature of all such Feynman diagrams is the VIRTUAL PARTICLE(s) being exchanged [created on one side and annihilated on the other] between the interacting particles. They are called "virtual" because they never manifest themselves directly outside the scattering region; of course, in most cases the same sorts of particles *can* be "knocked clear" of the collision by appropriate combinations of momenta, but then the diagram has a different topology. For instance, in Fig. 26.2 the right-hand diagram involves a simple rotation of the left-hand diagram by 90° and so it describes in some sense "the same physics" — but the process depicted, in which a positron and an electron "temporarily annihilate" into a photon and then that photon immediately converts into a new e^+e^- pair, is nominally quite different from the electron-electron scattering in the left diagram. Any $\mathcal{QED}$ adept would automatically think of both as being more or less the same thing.

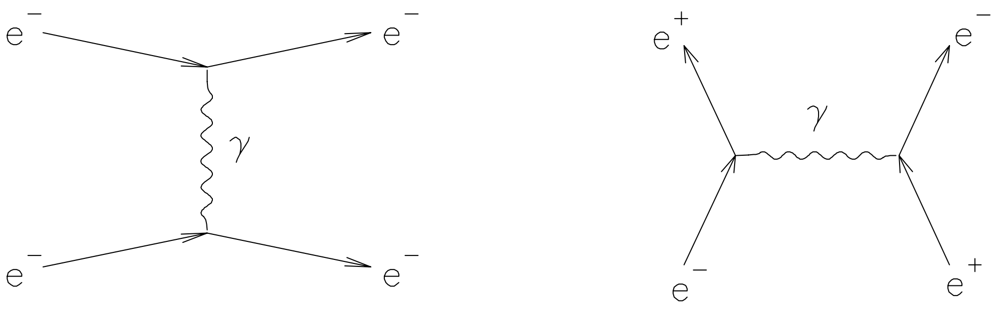

Figure 26.2 **Left**: Feynman diagram for electron-electron scattering by single photon exchange. **Right**: "CROSSING SYMMETRY" diagram for electron-positron scattering in the "s-channel" by virtual photon annihilation and pair production.

How is it possible to create a particle "out of nothing" as pictured in these diagrams? Only by virtue of the time-energy version of HEISENBERG'S UNCERTAINTY PRINCIPLE, which says that you can "cheat" energy conservation by an uncertainty ΔE, but only for a short time Δt such that

$$\Delta t \, \Delta E \; \geq \; \frac{\hbar}{2} \tag{1}$$

The bigger the "cheat," the shorter the time.

For photons, with no rest mass, a minimum of energy has to be "embezzled" from the "energy bank" to create a virtual photon; as a result it can travel as far as it needs to find another charged particle to absorb [annihilate] it. A heavier particle, on the other hand, cannot live for long without either being reabsorbed by the emitting particle or finding a receiver to annihilate it; otherwise the UNCERTAINTY PRINCIPLE is violated. This brings us back to Yukawa.

Around Yukawa's time every physicist knew that atomic nuclei were composed of NUCLEONS (protons and neutrons) confined to an extremely small volume. The problem with this picture is that the protons are all positively charged and the neutrons are (as the name suggests) neutral, so that such a nucleus entails keeping positive charges *very* close to each other — something that COULOMB REPULSION would rather they didn't do! Therefore (reasoned Yukawa) there must be a "STRONG" *attractive* force between NUCLEONS that was able to overpower the electrostatic repulsion.

But if the STRONG force were *long-range* like the ELECTROMAGNETIC force, then *all* nucleons *everywhere* would "reach out to someone" and fall together into one gigantic nucleus! This appears not to be the case, luckily for us. Therefore (reasoned Yukawa) the STRONG force must be *short-range*.

Now, we have just finished describing what would make a force have a short range — namely, the EXCLUSION PRINCIPLE: if the VIRTUAL QUANTA (particles) mediating the force are moderately *massive* [*i.e.*, "mesons"] then they require a big "cheat" of energy conservation to be created in the first place, and must be annihilated again very soon to have existed at all. Yukawa compared the known size of nuclei (about 10^{-15} m) with the UNCERTAINTY principle, assuming propagation at roughly the speed of light, and deduced that the mesons mediating the strong force must have a mass of about 130 MeV/c^2.

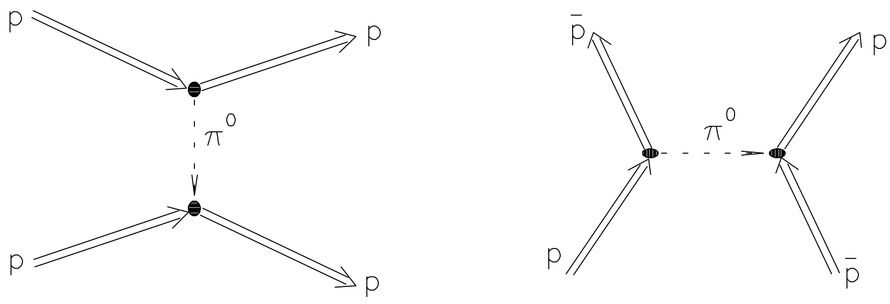

Figure 26.3 **Left**: Feynman diagram for proton-proton scattering by single pion exchange. **Right**: "Crossing symmetry" diagram for proton-antiproton scattering in the "*s*-channel" by virtual annihilation into a π^0 followed by proton pair production. Note the similarity with the Feynman diagrams for $\mathcal{QED}$, where the pion's rôle is played by a photon.

A few years later, muons were discovered in high-energy cosmic rays,[5] and the Physics world was quick to acclaim them as Yukawa's mesons. Unfortunately, they were wrong; the muon is a lepton, like the electron or the neutral neutrinos, which accounts for its penetration through the atmosphere (leptons do not interact strongly).[6] This quickly became clear, and shortly thereafter the true "nuclear glue" meson, the pion, was discovered in *very* high-altitude cosmic ray experiments and at the 184 inch Cyclotron in Berkeley. Then High Energy Physics began in earnest.

The Perturbation Paradigm Stumbles

It didn't take long for the theory of strong interactions to run into problems. The essence of the difficulty lies in the very word "strong." The strength of an interaction can be calibrated by the magnitude of the dimensionless *coupling constant* applied at each *vertex* [wherever a virtual particle is created or annihilated] in a Feynman diagram such as Fig. 26.1. As explained earlier, each such vertex in $\mathcal{QED}$ has a strength of $\alpha \approx \frac{1}{137}$, which makes "higher order diagrams" rapidly insignificant — great for calculating with a perturbation theory!

Unfortunately, the "strength" of a vertex in strong interactions is on the order of 1. This means that the single pion exchange diagram shown on the left in Fig. 26.3 or Fig. 26.4 is in principle *no more likely* than the incomprehensible mess on the right in Fig. 26.4, involving manifold exchanges of pions and other mesons, as well as creation and annihilation of baryon-antibaryon pairs.[7] Worse yet, *this is only one example* of the seemingly endless variety of possible diagrams one must in principle consider in order to make an accurate calculation of "simple" nucleon-nucleon scattering!

Of course, it wasn't *quite* that bad. Handy "sum rules" were discovered that explained why single pion exchange usually got you pretty close to the right answer, but *in principle* one had to make an almost infinitely difficult calculation in order to get the sort of *precise* predictions that Perturbation Theorists had come to expect from their experiences with $\mathcal{QED}$. Moreover, there were conceptual nightmares to sweat out — if you look closely at Fig. 26.4,

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[5] Muons are the main component of cosmic rays that make it to the Earth's surface — all the more strongly interacting particles are absorbed or re-scattered in the atmosphere, which makes a pretty good shield. In fact, if you take a transcontinental trip at 30,000 feet altitude, you pick up about 50 mR of ionizing radiation from cosmic rays that are *not* absorbed because you are above most of the shield!

[6] In case you wondered, I am skipping over a lot of agonizing reevaluation and painstaking experiments that led to the discoveries that justify using the "modern" names for all these particles; the muon was called a "mesotron" for years and is still sometimes referred to as a "mu meson" in the USSR. But why sacrifice simplicity for mere historical accuracy?

[7] I haven't bothered to label all the particles; see if you can find any violations of local conservation laws.

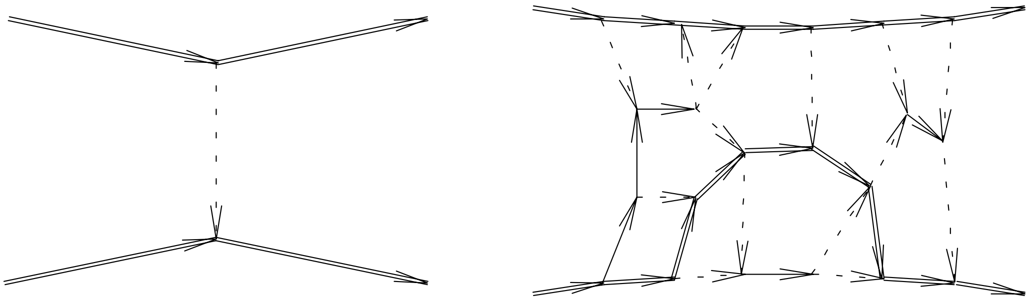

Figure 26.4 **Left**: Feynman diagram for single pion exchange. **Right**: A far more complicated Feynman diagram that is in principle no less important!

for instance, you will notice that a proton can emit a pion [OK, there are pions inside protons] which can turn into a proton-antiproton pair [OK, there are protons inside pions... Wait a minute!] and so on. Like many nightmares, this revealed an unexplored avenue of understanding: in the 1960's and 70's, Geoffrey Chew and his Theory group at Berkeley developed a non-perturbative theory of strong interactions that contained the "BOOTSTRAP PRINCIPLE:" every hadron is made up of combinations of all the other hadrons (and itself). Although I never could understand Chew's models, they represented a genuinely new paradigm that gained a good deal of purchase on the problem when suddenly the attention of the Particle Physics community was diverted by a revival of Perturbation Theory in the form of a QUARK model, about which I will say more later; since then Chew's approach has been sadly neglected, which I suspect is a great loss to Physics. Still, if we can get answers more easily by "recycling an old paradigm," the outcome is inevitable.

Weak Interactions

Skipping ahead to the 1980's, the virtual quanta mediating the WEAK INTERACTION (the force next weakest to the gravitational force) have only recently been identified directly in immense experiments at the biggest accelerators. These are the $W^{\pm}$ and Z^0 "INTERMEDIATE VECTOR BOSONS" whose masses are shown in Table 26.1.3. What can you conclude about the *range* of the WEAK INTERACTION?

In a unification of the WEAK and ELECTROMAGNETIC interactions that won acclaim for numerous theorists in the past two decades or so, the γ and the W and Z bosons have been shown to be merely different aspects of the same "ELECTROWEAK" force, despite their gross dissimilarities in mass and lifetime.[8]

26.1.4 The Zero-Body Problem

Before I depart from QUANTUM FIELD THEORY, let me point out a rather amusing consequence of being able to create almost anything you like out of nothing, provided you only do it for a very short time: As you may have heard, no one has ever found a completely satisfactory *general* solution for the THREE-BODY PROBLEM in Classical Mechanics — *i.e.*, the detailed behaviour of 3 particles all mutually interacting; however, the TWO-BODY PROBLEM (2 particles orbiting or scattering off one another) was "solved." RELATIVISTIC QUANTUM FIELD THEORY makes the 2-body problem into a *many*-body problem by virtue of all those virtual quanta being exchanged. Worse yet, the ONE-BODY PROBLEM (a single particle hanging around lonely in empty space) is similarly complicated by its tendency to emit

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[8] This theory now forms the core of what is known as "THE STANDARD MODEL" of elementary particles — a name which reveals a certain disaffection, since no one is particularly excited at the prospect of serving the Establishment prejudices connoted by a "standard model." Particle Physicists, like most free thinkers, prefer the self-image of a romantic revolutionary challenging established conventions and "standard models" everywhere. Not surprisingly, a great deal of experimental effort goes into "tests of the Standard Model" which the experimenters openly hope will throw a monkey wrench into the works.

Table 26.1 The INTERMEDIARY particles that convey various forces between other elementary particles.

Particle		**Mass** ($\mathrm{GeV/c^2}$)	**Interaction mediated**	**Lifetime** (s)
graviton	(?)	0	*gravity*	stable
photon	γ	0	*electromagnetism*	stable
vector boson	$W^\pm$	80.6	*weak*	2.93×10^{-25}
vector boson	Z^0	91.2	"	2.60×10^{-25}
pion (mainly)	π	0.139	*strong*	$\pi^\pm$: 2.6×10^{-8} π^0 : 8.3×10^{-17}
gluon	g	0?	*superstrong*	?
Higgs boson	H^0	> 24	*ultrastrong*	?
Higgs boson	$H^\pm$	> 35	"	?

and reabsorb a "cloud" of virtual quanta — not a trivial matter, since most "bare" particles are thought to acquire many of their "dressed" properties (such as mass) by virtue of such "renormalization."

Worst of all, the ZERO-BODY PROBLEM (*i.e.*, the vacuum) is now poorly understood, since there is truly *no such thing* as "empty space" — it is constantly filled with virtual electron-positron pairs (for example) popping into and out of existence, and these short-lived virtual quanta have the capacity to interact with each other and external particles! For example, there is a measurable effect on the H atom energy levels due to "VACUUM POLARIZATION," in which the virtual e^+e^- pairs actually notice the presence of passing "real" electrons and interact with them before disappearing again.[9]

Simple, eh?

26.1.5 The Seven(?) Forces

Although I have not yet defined what I mean by half the terms in Table 26.1.5, this is a convenient place to summarize the known and hypothetical interactions of matter. It is conventional to group "superweak"[10] together with the ELECTROWEAK interaction (which "unifies" the WEAK and ELECTROMAGNETIC forces) and to put "superstrong" and "ultrastrong" in with the STRONG interaction so that you should not be surprised to hear that there are only *three* "official" forces — gravity, electroweak and strong. However, there is a certain amount of freedom in semantics here. . . .

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[9] There is an even more dramatic consequence in the neighbourhood of a very small BLACK HOLE whose *tidal forces* (the *gradient* of the gravitational field between one place and another) is so intense that one of the virtual particles of a pair can fall into the black hole while the other is ejected and becomes a "real" particle — leading to intense radiation that can be described as the *explosive annihilation* of the miniature black hole. This explains why there are no *small* black holes around any more, only *big* ones whose gravitational gradient is very gentle at the Schwartzschild radius. I will define these terms in the Chapter on GENERAL RELATIVITY.

[10] The "superweak" force is a name coined to describe a *really* esoteric interaction which appears to affect *only* the decays of strange neutral mesons (if it exists at all).

Table 26.2 Interactions of the elementary particles. A "yes" means that the types of particle indicated at the left are directly coupled to the force above; "no" means the opposite; three asterisks ($* * *$) means that the particle in question is the *intermediary* for that force.

PARTICLE(s)		Gravity	Super-weak	Weak	Electro-magnetic	Strong	Super-strong	Ultra-strong
gravitons		$* * *$						
photons	γ	yes	?	no	$* * *$	no	no	no
neutrinos	ν_e, ν_μ, ν_τ	yes	?	yes	no	no	no	no
leptons	e, μ, τ	yes	?	yes	yes	no	no	no
mesons	$\pi, K, \ldots$	yes	?	yes	yes	yes	no	no
baryons	$p, n, \Lambda, \ldots$	yes	?	yes	yes	yes	no	no
neutral kaons	$K^0, \bar{K}^0$	yes	yes	yes	yes	yes	no	no
vector bosons	W, Z	yes	?	$* * *$	yes	no	no	no
quarks	u, d, s, c, b, t	yes	?	yes	yes	no	yes	no
gluons	g	yes					$* * *$	
(hypothetical)	T, V	yes						yes
Higgs bosons	H	yes	?					$* * *$
Relative strength		10^{-40}	?	10^{-4}	$\frac{1}{137}$	1	10-100	$> 10^{10}$?

26.1.6 Particle Detectors

Turning back to the hardware of High Energy Physics (HEP), I should point out that it is not enough to build accelerators capable of delivering enough energy to a collision to create more massive and more exotic particles — one must also have some way to "see" those particles once they are created. This is in principle rather challenging, since they are all apt to be moving at near light speed and are certainly too small to detect with visible light; moreover, usually they don't last very long — the heavier the particle, the larger the variety of lighter particles into which it might decay! This rule-of-thumb works quite well in general, so that exceptions (long-lived heavy particles) stand out rather dramatically; more on this later.

In practice it is surprisingly easy to "see" elementary particles, once you get used to a new way of "seeing." The basis of all particle detectors is that *charged* particles cause *ionization* where they pass through matter.[11] The ions they leave behind form a "track" that can be detected in several ways.

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[11] Neutral particles either convert into charged particles (which do ionize the medium) or else are conspicuous in their invisibility!

Scintillating!

The "workhorse" of experimental HEP is the *scintillation counter*. This simple device works as follows: the ionization of certain types of molecules causes photochemical reactions that liberate visible light called "scintillation" light.[12] This light is conveyed through a clear liquid, plastic or crystalline matrix, bouncing off polished exterior surfaces *via* total internal reflection until it reaches the *photocathode* of a vacuum tube where the photons liberate electrons *via* the PHOTOELECTRIC EFFECT. These electrons are then accelerated by high voltages in the tube until they strike a "first dynode" where each electron knocks loose about ten additional electrons which are accelerated in turn to the "second dynode" where they in turn each knock loose another ten electrons each, and so on down a cascade of up to 18 dynodes. As a result, that one electron originally liberated by the incoming photon can produce a pulse of 10^{18} electrons at the "anode" or the tube, which is (mnemonically, for once) called a PHOTOMULTIPLIER TUBE. These amazing devices have been refined over a period of nearly half a century until some have "quantum efficiencies" approaching 100% (they can fairly reliably detect *single photons*) and (most importantly) generate electrical pulses a few ns (nanoseconds, billionths of a second) wide whose arrival at a bank of fast electronics is correlated with the time the original ionizing particle hit the detector within a fraction of a ns. This means High Energy Physicists can routinely do *timing* with a resolution comparable to the length of time it takes light to go 10 cm! Without this impressive *timing* capability it would be very difficult to do *any* modern HEP experiments. Interestingly enough, this part of the technology has not improved significantly in several decades.

Clouds, Bubbles and Wires

Although one can build arrays of scintillation counters that act like "pixels" in computer graphics and can tell where particles go within an uncertainty of the size of the individual counters, this is very expensive and not usually very precise. Moreover, it was not how the business of "tracking" elementary particles got started.

The earliest "position-sensitive detectors" took advantage of the tendency of liquid droplets to form (or "nucleate") on *ions* when a gas (like air) is "supersaturated" with a vapour (like water or alcohol) that would like to precipitate but can't quite make up its mind where to start. The result, once the process is finished, is a *cloud* of liquid droplets, hence the name "CLOUD CHAMBER." But this final state is not very useful. It is the situation *just after a fast ionizing particle passes through* the saturated gas that is interesting — the left-behind *ions* nucleate a trail of liquid droplets like a string of beads, and one can see (and/or take a picture of) that trail at that moment, to "see the track" of the particle. If it is passing through a magnetic field, the *curvature* of the track reveals its *momentum* and the *density* of the track reveals its *charge* and its *speed*, from which one learns its mass and just about everything about it that can be measured directly. This device was used for many of the early cosmic ray experiments.

The trouble with CLOUD CHAMBERS is that they don't have very fine resolution and the droplets start *falling* as soon as they form. Moreover, even a saturated gas has a rather low density, so if one is looking for interactions of a beam particle with other nuclei the events are spread out over too large a volume to photograph efficiently. Another method still used today is to place a stack of PHOTOGRAPHIC EMULSIONS in the path of the beam and to examine the resulting tracks of silver particles created by the ionizing particle. The problem with this technique is that the emulsion is not reusable — one "takes an exposure" and then the emulsions must be dissected and painstakingly examined with a microscope. Too much work. What was really needed was a sort of "high density cloud chamber" that "healed" soon after each track had been photographed.

The apocryphal story is that a HEP experimenter sat staring glumly into his beer glass one night after wishing for such a device, and noticed that the bubbles always seemed to form in the same places. He sprinkled in a few grains of salt and, sure enough, the bubbles formed on the salt grains. "Eureka!" he cried, leaping up, "the bubbles form on *ions*!" And off he went to build the first bubble chamber.[13]

The idea of the BUBBLE CHAMBER is that a liquid (usually liquid hydrogen) can be abruptly *decompressed*, causing

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[12] One example is old-fashioned "mothballs" — if you take a handful of mothballs into a very dark closet (you must get rid of *all* ambient light!) and wait for your eyes to adjust, you should be able to see tiny flashes of light every few seconds as cosmic ray muons zap the mothballs. There are many apocryphal stories about graduate students in closets with mothballs and manual counters in the early days of nuclear physics....

[13] Probably this was a bar frequented by many HEP types, so such behaviour went unremarked.

it to "want" to boil, but (like the supersaturated vapour) it can't make up its mind where to start first.[14] If the decompression is done just as ionizing particles pass through the liquid, the ions in their tracks will nucleate the first bubbles of vapour and a clear, sharp track can be seen and photographed; then the liquid is quickly recompressed, the bubbles go away, and the chamber is ready for another "event."

Such liquid hydrogen BUBBLE CHAMBERS are still in use today, but they had their heyday back in the 1950's and 1960's when higher energy accelerators introduced Particle Physicists to the "Hadron Zoo" of strongly-interacting particles. The most gratifying aspect of a bubble chamber picture is that you can make a big copy of it and put it on your wall, where anyone can point to the different tracks and say, "There goes a pion," or, "This short gap here is a Lambda." The picture appeals to the all-important Visual Cortex, leading to such familiar phrases as, "Seeing is believing," and, "A picture is worth a thousand words." [I won't attack these comforting myths this time; I like bubble chamber pictures too!]

The trouble came when experimenters set out to *measure* the curvatures and densities of millions of tracks in bubble chamber pictures. This involves more than just patience; in the 1960's an army of "scanners" was hired by the big HEP labs to filter hundreds of thousands of bubble chamber pictures looking for certain topological configurations of tracks that were of interest to the experimenter; a lexicon of "vees" and "three-prongs" was built up and eventually these people could recognize events containing different types of elementary particles more efficiently than any Physicist — for, almost without exception, the scanners were nonscientists selected for their rare talents of patience and pattern recognition. It was a fascinating sociological phenomenon, but it cost enormous sums for the salaries of these people and Physicists would always rather buy fancy equipment than create mere jobs. So, as electronics and computers grew in power and shrank in price, it was inevitable that the experiments pressing the limits of HEP technology would seek an "electronic bubble chamber" that could be read out, analyzed and tabulated all by computers.

The result was the WIRE CHAMBER, which again uses the ionization caused by charged particles but this time detects the ion's charges directly with sensitive electronics. There are many versions of this technology, but almost all involve thousands of tiny *wires* strung through a target volume at extremely precise positions and maintained at high voltage so that any ions formed will drift toward one or more of the wires and form a pulse that can be read out at the ends of the wire and interpreted. Such devices can "track" particles through huge volumes to a fraction of a mm and can analyze hundreds or even thousands of events per second, with one "event" containing dozens or even hundreds of particle tracks.

Today's large HEP experiments all involve scintillation counters, wire chamber arrays and other components, each especially sensitive to one or another type of particles, and require on-line computers that must be built specially to handle the enormous flow of information;[15] an ubiquitous feature of *really* high energy particle physics is that there are enormous numbers of particles in the "final state" after two extremely high energy projectiles collide head-on. It is easy to see why this is: the more energy you have, the more mass you can create. It also follows that the heavier the particle, the more ways it has to decay, so the heaviest particles should have the shortest lifetimes. When this rule is *not* obeyed, we have cause to get suspicious.

26.2 Why Do They Live So Long?

If a heavy particle is free to decay into lighter particles, then why isn't the universe filled with *only* the lightest particles? Why, for instance, doesn't an electron (mass 0.511 MeV/c^2) decay into photons (zero mass), with the excess mass appearing as kinetic energy? Well, to begin with, the electron has "spin $\frac{1}{2}$" (*i.e.*, an intrinsic angular

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[14] If you have access to a microwave oven, you can observe this effect for yourself: take a cup of cold water and slowly increase the cooking time (replacing it with new cold water each time) until it is just starting to boil as the timer runs out. Then do one more with a slightly decreased cooking time, take out the cup and drop in a few grains of sugar or salt — the dissolved gases will abruptly come out of solution around these "nucleation centres" to make a stream of bubbles for a short time.

[15] For decades, HEP has "driven" the leading edge of supercomputer hardware and software development. Today's computing environment is rapidly becoming more driven by the personal workstation, which is probably a more healthy arrangement, but it is certainly true that we would not have the computer technology we do without the demand created by HEP from about 1950 to about 1980.

momentum of $\frac{1}{2}\hbar$), while a photon has "spin 1" (*i.e.*, 1 $\hbar$). There is no way to combine several spin 1 objects to make a spin $\frac{1}{2}$ object, so ANGULAR MOMENTUM CONSERVATION forbids an electron to decay into photons. What else? Well, the electron is *charged*, and the photons aren't! So what? Well, electric charge Q is a CONSERVED QUANTITY — not only is the total amount of charge in the universe constant, but the net charge *in any reaction* must also remain unchanged *at every step*.

OK, the electron is stable. But why can't the *proton* decay into a *positron* (the antiparticle of an electron), which has the same charge and the same spin as the proton? It could also give off two photons with opposite spins, satisfying all the criteria mentioned so far. Well, protons must have some special property that we will call BARYON NUMBER because only *heavy* particles like the proton have it. So far as we know, baryon number manifests itself *only* as a CONSERVED QUANTITY in the interactions of elementary particles. We define the baryon number of a proton to be 1 and that of electrons and photons to be zero. Baryon number is conserved just like electric charge, and this accounts for the stability of protons: the proton is the lightest baryon, so there is nothing for it to decay into!

The next lightest baryon is the *neutron*, and it does indeed decay (slowly) into a proton, an electron (to compensate for the charge of the proton) and an electron antineutrino to compensate for the electron number.[16] Huh? What's "ELECTRON NUMBER?" It's yet another CONSERVED QUANTITY that the *weak interaction* governing neutron decay has to keep account of. We know it exists only because neutrons *don't* decay into just a proton and an electron. The electron NEUTRINO is a sort of chargeless, *massless* version of an electron that has almost no interaction with matter at all — a typical neutrino can pass through the Earth (and a lot more planets besides!) without much chance of touching anything!

How about MUONS? Everyone says these are "sort of like heavy electrons," so why can't a muon decay into an electron and a photon?[17] The muon *does* decay into an electron plus an electron antineutrino and a muon neutrino, but *not* into an electron and a photon. This is because the muon has another different CONSERVED QUANTITY called — you guessed it – MUON NUMBER which is a different FLAVOUR[18] from ELECTRON NUMBER. Naturally, the muon NEUTRINO has muon number too, and is therefore unmistakable for an *electron* neutrino. But only because it never appears where an electron neutrino might.

Is all this perfectly clear? No? I don't blame you. Just remember, whenever a particle refuses to decay into lighter particles for no apparent reason, it is presumed to be because of some new CONSERVED QUANTITY that one has and the others don't. The assignment of names to these ephemeral quantities which Nature seems to hold in such reverence is pretty much arbitrary, so their "discoverers" get to think up names they think are mnemonic, allusive or just cute. There are some examples that are a little embarrassing.

For instance, while discovering hordes of new short-lived heavy particles in the 1950's, people ran across a heavy, spinless, uncharged particle called the neutral KAON which decayed (as expected) into lighter PIONS but *very slowly*, suggesting that kaons must have some new property which the STRONG interaction (that should make kaons decay *very rapidly* into pions) could not "violate" but the WEAK interaction could. This new quantity, conserved in strong interactions but not necessarily in weak interactions, was called "STRANGENESS" for reasons that were obvious but hopelessly parochial. I hate this one, because it takes over a perfectly good English word that one might want to use in the same sentence.[19]

It gets worse. But I have introduced far too many new particles and mentioned far too many jargoney names without explaining what they are supposed to mean; I will come back to the literary tastes of Particle Physicists after I have outlined some of the currently used classification schemes.

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[16] It just barely makes it, mass-wise, which partly accounts for the slowness of the decay.

[17] As a matter of fact, this is still an open question — experiments have recently pushed the upper limit on the "branching ratio" for $\mu \to e\gamma$ (*i.e.*, the fraction of the time muons decay into electrons and photons) to less than one part in 10^{11} and more experiments are underway, because several theories demand that such "flavour-violating" decays must exist at some level.

[18] No, I'm not kidding, the official name for the difference between muons and electrons (and, later on, TAU leptons) is "lepton FLAVOUR."

[19] Kirk: "Boy, this particle sure looks *strange*." Spock: "Not at all, Captain. If you look more closely, I believe you'll find it's *charmed*."

26.3 Particle Taxonomy

The most efficient classification scheme is a succession of *orthogonal binary dichotomies* in which (if possible) roughly half the items to be classified go on each side of every successive distinction. These may be drawn as "Venn diagrams" in which a circle (representing everything) has a line drawn through the middle.

The first distinction does not even come close to splitting up all the "elementary" particles into two equal groups, but at least it is *unequivocal*. This is the question of whether the particle is strongly interacting or not. If it is affected by the strong interaction, it is called a hadron. If *not*, it is called a lepton. [Both of these have Greek roots. Look them up if you're curious.]

26.3.1 Leptons

The leptons make a short list and are easy to classify by the three known "flavours" — e, μ and τ. Each type experiences gravity, the electroweak interaction and apparently nothing else.

Table 26.3 The leptons (particles with only weak and sometimes electromagnetic interactions). All leptons have spin $\mathcal{J} = \frac{1}{2}\hbar$ and are therefore *fermions*. Each "generation" of lepton has its own distinctive "flavour" (electron, muon, tau) and is governed by its own conserved "lepton number." For each particle there corresponds an *antiparticle* of the same mass and spin but with opposite values of electric charge and lepton number of the corresponding flavour.

PARTICLE(s)		**Mass** (MeV/c^2)	**Charge** $\mathcal{Q}/e$	**Lifetime** (s)	**Principle Decay Modes**
electron	e	0.511	-1	$> 6 \times 10^{29}$	none
e neutrino	ν_e	$< 1.7 \times 10^{-5}$	0	∞	none
muon	μ	105.66	-1	2.2×10^{-6}	$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$ $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$
μ neutrino	ν_μ	< 0.27	0	∞	none
tau	τ	1784	-1	3.03×10^{-13}	$\tau^- \rightarrow (\mu, e)^- + \bar{\nu}_{(\mu,e)} + \nu_\tau$ $\tau^- \rightarrow (\text{hadron})^- + (\text{neutrals}) + \nu_\tau$
τ neutrino	ν_τ	< 35	0	∞	none

26.3.2 Hadrons

The remaining strongly-interacting hadrons make a huge "zoo" of mostly short-lived particles of almost every shape and size. However, these too can be separated cleanly into two dichotomous categories: the half-integer spin baryons (so named because they tend to be more *heavy*), which are all fermions — *i.e.*, each type obeys its own version of the Pauli exclusion principle — and the zero or integer spin mesons (so named because they tend to me *medium* heavy), which are all bosons — *i.e.*, you can put as many as you like in the same state at the same time. We now know lots of interesting things about the baryons and mesons, but the modern *definitions* of these classes of hadrons are in terms of their *spins*.

Integer spin hadrons are bosons and are all called *mesons*; Half-integer spin hadrons are fermions; those which are not *quarks* are called *baryons*. All baryons have a "baryon number" $\mathcal{B} = 1$; mesons have none. The "hypercharge" $\mathcal{Y}$ of a particle is the sum of its baryon number and its strangeness: $\mathcal{Y} = \mathcal{B} + \mathcal{S}$. Quarks all have $\mathcal{B} = \frac{1}{3}$ as well as fractional electric charge because it takes 3 to make one baryon; otherwise they follow the same rules. For each

Table 26.4 Some of the HADRONS (strongly interacting particles).

Name		**Mass** (MeV/c^2)	**Lifetime** (s)	**Spin** $\mathcal{J}^{\mathcal{P}}$ [$\hbar$]	**Charge** $\mathcal{Q}/e$	**Isospin** $\mathcal{I}$	**Strangeness** $\mathcal{S}$
QUARKS:							
"up"	u	411?	∞?	$\frac{1}{2}$	$+\frac{2}{3}$	$\frac{1}{2}$	0
"down"	d	411?	∞?	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{2}$	0
"strange"	s	558?	∞?	$\frac{1}{2}$	$-\frac{1}{3}$	0	-1
MESONS:							
pion	π	139	$\pi^{\pm}:\ 2.6 \times 10^{-8}$ $\pi^0:\ 8.3 \times 10^{-17}$	0^-	$-1, 0, +1$	1	0
kaon	K	495	$K^{\pm}:\ 1.2 \times 10^{-8}$ $K^0:$ ambiguous	0^-	$-1, 0, +1$	$\frac{1}{2}$	$K^0, K^+:\ +1$ $\bar{K}^0, K^-:\ -1$
eta	η	549	8.9×10^{-15}	0^-	0	0	0
rho	ρ	770	4.3×10^{-24}	1^-	$-1, 0, +1$	1	0
omega	ω	783	6.58×10^{-23}	1^-	0	0	0
phi	ϕ	1020	1.6×10^{-22}	0^-	0	0	0
	K^*	892	1.33×10^{-23}	1^-	$-1, 0, +1$	$\frac{1}{2}$	$K^{*0}, K^{*+}:\ +1$ $\bar{K}^{*0}, K^{*-}:\ -1$
	⋮	⋮	⋮	⋮	⋮	⋮	⋮
BARYONS:							
nucleon	N	938	proton (p) : ∞ neutron (n) : 920	$\frac{1}{2}^+$	$0, +1$	$\frac{1}{2}$	0
lambda	Λ	1116	2.6×10^{-10}	$\frac{1}{2}^+$	0	0	-1
sigma	Σ	1190	$\Sigma^{\pm} :\approx 10^{-10}$ $\Sigma^0 :< 10^{-14}$	$\frac{1}{2}^+$	$-1, 0, +1$	1	-1
cascade	Ξ	1320	$\approx 2 \times 10^{-10}$	$\frac{1}{2}^+$	$-1, 0$	$\frac{1}{2}$	-2
	⋮	⋮	⋮	⋮	⋮	⋮	⋮
delta	Δ	1232	5×10^{-24}	$\frac{3}{2}^+$	$-1, 0, +1, +2$	$\frac{3}{2}$	0
	Σ^*	1383	1.6×10^{-23}	$\frac{3}{2}^+$	$-1, 0, +1$	1	-1
	Ξ^*	1530	6.6×10^{-23}	$\frac{3}{2}^+$	$-1, 0$	$\frac{1}{2}$	-2
Omega	Ω	1672	1.3×10^{-10}	$\frac{3}{2}^+$	-1	0	-3
	⋮	⋮	⋮	⋮	⋮	⋮	⋮

particle (including quarks) there corresponds an *antiparticle* of the same mass, spin, parity and isospin, but with opposite values of electric charge, strangeness, baryon number and hypercharge.

Generally speaking, all the heavy hadrons are *very short-lived* because the interaction governing their decay into lighter hadrons is, after all, *strong*. I have already mentioned a notable exception to this rule, namely the *strange mesons*, which take far longer than they should to decay into pions. In the 1950's this led to the coining of the term STRANGENESS to describe that strange (grrr...) property of K mesons (for instance) that could not be "swept under the rug" by the strong interaction. By checking to see what other particles *could* decay into kaons, and in the company of what else, a STRANGENESS was assigned to each of the hadrons. Then a strange [Oops! Can't use that!] — an odd [Ouch! That implies a PARITY quantum number] — a peculiar [Whew!] pattern began to manifest itself when the particles were grouped together according to the known *quantifiable properties* of SPIN, CHARGE, STRANGENESS and MASS.

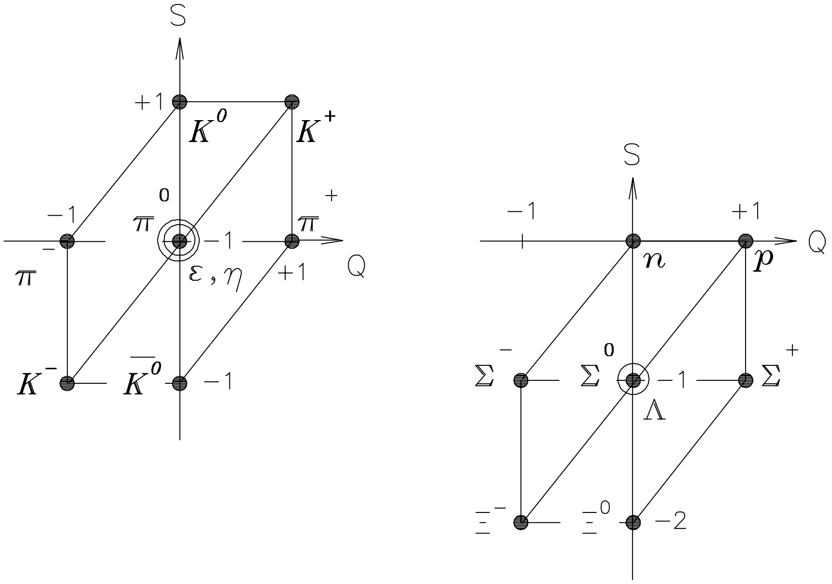

Figure 26.5 Murray Gell-Mann's "Eightfold Way." **Left**: the SCALAR MESONS. **Right**: the SPIN-$\frac{1}{2}$ BARYONS. Note the striking similarity of the grouping when strangeness $\mathcal{S}$ is plotted against charge $\mathcal{Q}$. The VECTOR (spin 1) MESONS form a group exactly like the SCALAR MESONS on the left, further reinforcing the pattern.

The various hadrons are first separated into collections that all have the same *spin*, such as the SCALAR [zero spin] MESONS or the VECTOR [spin 1] MESONS or the SPIN-$\frac{1}{2}$ BARYONS or the SPIN-$\frac{3}{2}$ BARYONS. It is immediately evident that the *masses* of all the particles in any one of these groups are roughly similar, whereas two different groups tend to have significantly different masses. This arouses some suspicion. Then we notice that, within these groups, the particles with the most *strangeness* tend to be the *heaviest*.

Next we notice that if we *plot* the particles in a group on a graph of the two other quantifiable properties — charge $\mathcal{Q}$ and strangeness $\mathcal{S}$ — they form arrangements that are remarkably *similar* in shape![20] The hexagonal arrangement with two particles at the centre appears in each of the first three groupings listed above; Murray Gell-Mann decided that THIS MUST MEAN SOMETHING about the *constituents* of these particles, just as the regular groupings of elements in the PERIODIC TABLE meant something about the constituents of *atoms*. Because of the number of particles in the pattern, because of his eclectic intellect and because he wanted to make up a catchy name for his theory that people would want to talk about just to sound savvy, Murray named this pattern the EIGHTFOLD WAY after the spiritual/behavioural prescription in Buddhism. More cuteness.

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[20] The shapes are a little crooked in this representation. The HYPERCHARGE $\mathcal{Y}$ and ISOSPIN $\mathcal{I}$ (whose "projection" $\mathcal{I}_3$ along God-only-knows what axis is the same as its charge $\mathcal{Q}$, within a constant) were invented partly to make the diagrams of $\mathcal{Y}$ *vs.* $\mathcal{I}_3$ nicely symmetric with the origin at the centre of each arrangement. I haven't bothered.

26.3.3 Quarks

Fair enough, obviously these *symmetries* were trying to tell us something about the composition of hadrons. What? Well, needless to say, Gell-Mann *et al.* did not immediately come up with a simple nuts-and-bolts assembly manual; instead, they developed an abstract mathematical description called $SU(3)$ analogous to the description of *spin* for electrons, $SU(2)$. [If you're interested, the acronym stands for *S*imple *U*nitary group of order 2 or 3.] I won't attempt to elaborate, but you can see why something like this was needed — as for the $\hat{z}$ component of spin, the projections of the three $SU(3)$ operators along God-only-knows what axes in God-only-knows what dimensions[21] cannot have a continuum of possible values but only a fixed number of discrete or *quantized* values. What is *actually refers to* is totally unknown. Or, more properly, it refers to just what it says; if that means nothing to us, well, that's just because our empirical personal experience of the space of $SU(3)$ is so limited that we don't relate to it very well. What do "normal" space and time *actually refer to*?

Anyway, someone inevitably formulated a simpler instruction manual for assembling hadrons. This was to give the requisite properties to three (there are more now, but hold off on that) *really* fundamental *component* particles called "QUARKS."[22] All MESONS are composed of a *quark-antiquark pair* whereas BARYONS are composed of *three quarks* held together by a "SUPERSTRONG" force mediated by a new type of intermediary called "GLUONS" (g) [more cuteness, but who can argue. . .].

Table 26.5 The known (or suspected) "generations" of QUARKS All quarks have a "baryon number" $\mathcal{B} = \frac{1}{3}$ as well as fractional electric charge because it takes 3 to make one baryon. The "hypercharge" $\mathcal{Y}$ of any particle is the sum of its baryon number and its strangeness: $\mathcal{Y} = \mathcal{B} + \mathcal{S}$. For each quark there corresponds an *antiquark* of the same mass, spin, parity and isospin, but with opposite values of electric charge, strangeness, baryon number and hypercharge.

Name		**Mass** (MeV/c^2)	**Lifetime** (s)	**Spin** $\mathcal{J}^{\mathcal{P}}$ [$\hbar$]	**Charge** $\mathcal{Q}/e$	**Isospin** $\mathcal{I}$	**Strangeness** $\mathcal{S}$
"up"	u	411?	∞?	$\frac{1}{2}$	$+\frac{2}{3}$	$\frac{1}{2}$	0
"down"	d	411?	∞?	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{2}$	0
"strange"	s	558?	∞?	$\frac{1}{2}$	$-\frac{1}{3}$	0	-1
"charm"	c	$\geq$ 1500?	∞?	$\frac{1}{2}$	$+\frac{2}{3}$	0	0
"bottom"	b	?	∞?	$\frac{1}{2}$	$-\frac{1}{3}$	0	0
"top"	t	?	∞?	$\frac{1}{2}$	$+\frac{2}{3}$	0	0
$c\bar{c}$	J/ψ	3100	0.97×10^{-20}	1^-	0	0	0
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

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[21] Honest, we don't have the faintest idea whether there is actually some *space* in which ISOSPIN actually refers to *rotations* about some *axis*, we only know that isospin *transforms that way*. If there is such a space, none of its dimensions are our familiar x, y or z directions. Very weird.

[22] See James Joyce's *Finnegan's Wake* for the origin of the term "quark" — it was originally a nonsense syllable, which makes it a pretty good choice for its present application. At least the commandeering of the word "quark" by Particle Physics did not inconvenience any users of the English language.

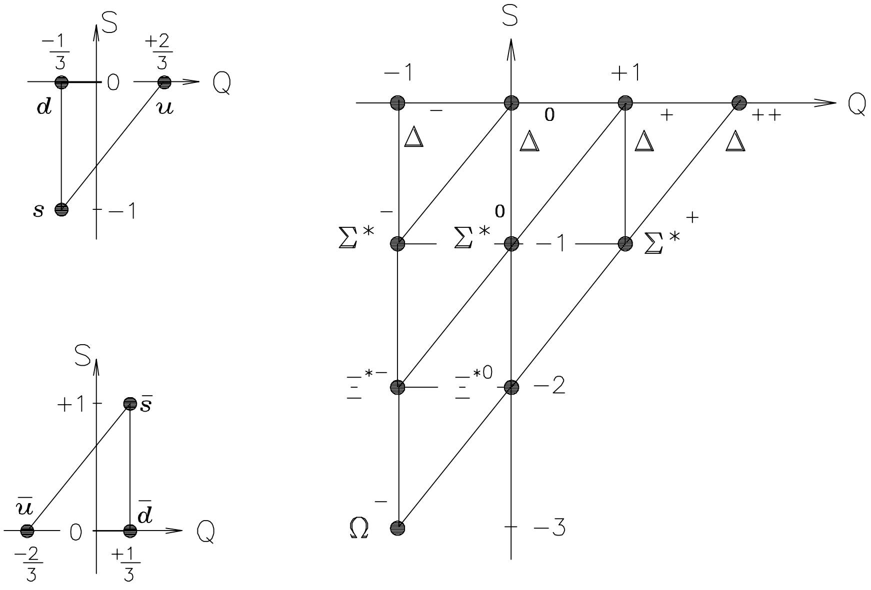

Figure 26.6 Upper left: the three lowest-mass QUARKS. Lower left: the corresponding ANTIQUARKS. Right: the SPIN-$\frac{3}{2}$ BARYONS. The Ω^- (strangeness -3) was predicted by a "quark content" analysis and later found experimentally, convincing everyone that the $SU(3)$ model was correct.

Colour

The three original quarks are "up" (u), "down" (d) and of course "strange" (s). Each is a spin-$\frac{1}{2}$ FERMION but it took some time to understand how three similar quarks could coexist in the same state within a baryon. (The extension of the PAULI EXCLUSION PRINCIPLE forbids this.) The resolution of this dilemma was to propose (and later believe) that *each* quark comes in three different complementary "COLOURS" (call them red, green and blue) that have to be combined to make the composite particle (meson or baryon) *colourless* (white) just the way the three colours on a TV monitor must all be lit up at once to produce a white "pixel." Of course, we have no idea what COLOUR *is* — it certainly has nothing whatsoever to do with the wavelengths of visible light! — but by now you should be comfortably disconnected from the world of empirical personal experience, so the fact that the metaphor of colour gives us a handy way of getting right answers should suffice.

Using this *quark model* with *gluon exchange* [gluons are *colour changers*, they convert a quark from one colour to another when emitted or absorbed] in a fashion exactly analogous to $\mathcal{QED}$, theorists are now able to accurately describe much of the structure of hadrons, thereby rescuing PERTURBATION THEORY from the ashes of strong interactions, where it failed miserably.[23] The new theory inevitably became known as Quantum ChromoDynamics (or $\mathcal{QCD}$) by analogy with $\mathcal{QED}$ except with colour (Greek *chromos*) in place of electric charge.

Why Quarks are Hidden

If quarks are "real" particles and not just a cute mnemonic metaphor for some esoteric mathematics,[24] we ought to be able to "see" one in a bubble chamber or other device "watching" a high energy scattering event. Unfortunately,

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[23] Unfortunately, the genuinely new paradigms that were springing up to deal with this crisis (*e.g.* Geoffrey Chew's BOOTSTRAP THEORY, in which each hadron is composed of small amounts of all the others [think about it!]) have been neglected since the development of $\mathcal{QCD}$.

[24] Of course, ENERGY is "just a cute mnemonic metaphor for some esoteric mathematics," if we think back to Classical Mechanics; but we have gotten so used to ENERGY that we don't think of it that way any more, whereas QUARKS are still. . . well, *weird*.

this can never be. The reason is intriguing.

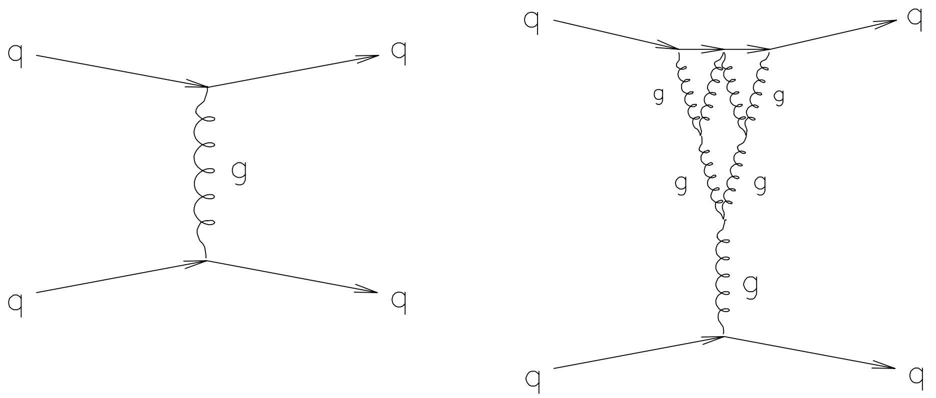

Figure 26.7 **Left**: $\mathcal{QCD}$ in first order — two quarks exchange a single GLUON at close range. **Right**: if the two quarks get too far apart, the original gluon gets an chance to *branch* into several gluons, strengthening the attractive force.

The "SUPERSTRONG" force between quarks is transmitted by the exchange of GLUONS [a nice descriptive name, for once!] which are massless, like photons, but have one trick up their sleeves that photons don't: they can "branch" (one gluon coupling to two gluons, and so on) if given enough room. Thus, while the electromagnetic force drops off as $1/r^2$, the SUPERSTRONG or $\mathcal{QCD}$ force actually *increases* with increasing distance between the two quarks! Once the distance gets big enough — as in a high-energy collision — the energy stored in the gluon field is so intense that quark-antiquark *pairs* are created out of the vacuum between the quarks and the original quark grabs the new antiquark to become a MESON, while the new quark takes the place of the old one in the hadron that has collided.

Thus, try as we might, we can never create a free quark. We can never "see" these ubiquitous particles that make up everything around us except leptons. This is very frustrating and for years led many Particle Physicists to insist that quarks were just figments of theorists' imaginations. But of course the paradigm works too well to be abandoned and the skeptics have by now pretty much given up.

26.4 More Quarks

Elementary Particle Physics seemed to be "converging" at last on a simple description in terms of a manageable number of *really elementary* constituents until around 1964, when some rogues suggested that if there were 6 leptons (counting the neutrinos) then there ought to be 6 quarks too, Nature being endowed with frugality and æsthetics just like Mathematicians. Actually the argument may have been more convincing than that, but I didn't understand it. This might not have raised many eyebrows except that in 1974 two huge groups of Particle Physicists led by Burton Richter and Samuel Ting *simultaneously* (or so close that no one could claim the other had stolen the idea) discovered a new meson that was both very heavy (3100 MeV/c^2) and extremely stable (0.97×10^{-20} s). [Well, for a particle that *heavy*, 10^{-20} s is a *long* time!] This particle, which has the unique disadvantage of *two names* — J and ψ — because of the unusual circumstances of its discovery and the enormous egos required for undertaking and directing such huge experiments, was immediately recognized to be the manifestation of a new kind of quark, the c quark, which had yet another weird property conserved by strong interactions. In an unsuccessful attempt to compensate for the callousness with which useful words had been ripped off from the English language in the past, the new property was named (groan) "CHARM."

Now there is a whole new *menagerie* of CHARMED particles to complicate matters; and (skipping ahead to today) another[25] of the predicted 6 quarks has been found as well. It is the b quark, and what the "b" stands for makes an interesting story.

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[25] A Fermilab consortium has also announced a "body of evidence" for the sixth and heaviest quark, the t quark. Most

The final[26] two quarks were originally posited to manifest two additional conserved properties called TRUTH (t) and BEAUTY (b). This, however, was too much even for the Particle Physics community. Whether we were finally exercising some restraint or had merely become embarrassed by newspaper headlines reading, "CERN Physicists hunt for Naked Bottom," or "Still no Truth in Quark Hunts," shall never be known. It was, however, decided to retroactively change the names of the new quarks (and their corresponding properties) to "TOP" and "BOTTOM" — which, you will note, have the same first letter as the old names, so that the old publications written by Particle Physicists who forbear to use the full names were still valid.

Now, personally, I think this was a mistake. No one is fooled by this attempt to pretend Particle Physicists are not crazy megalomaniacs, and now we have to try to remember the difference between UP-DOWN and TOP-BOTTOM. Perhaps newly discovered particles should be submitted to a panel of English scholars for naming, but this would take some of the fun out of Particle Physics, and if it isn't fun then what is there to keep it going? Hmmm. . . .

26.5 Where Will It End?

Many people have been quick to point out that things don't ever seem to get any better. First we had the elements to explain, then nuclei; there was a pleasant time when the world consisted only of photons, electrons, neutrinos, protons, neutrons and pions — but we had to spoil it by looking more closely and making higher energy accelerators. Then the "hadron zoo" collapsed to three quarks and the gluon, and things were looking up again; but now there are *six* quarks (one of which, the t, still hasn't been observed) and as many leptons, and at least 4 different intermediaries.

Is this just another round of simplification followed by more complexity at a deeper level? Possibly. It has been proposed that quarks and leptons may themselves be composite particles, and further that every particle must have a "SUPERSYMMETRIC" (or "SUSY") partner with the opposite sort of *statistics* — for each fermion there must be a supersymmetric boson, and *vice versa.*[27] There is no shortage of new theories, nor is arrogance in short supply — one model called "SUPERSTRINGS" has been touted as a TOE (Theory Of Everything) by the New York Times (which loves to get into these debates).[28] There is, however, a small *practical* problem.

All the Grand Unification Theories (or GUTs) predict wonderful simplifications at enormously high energies on the scale of the first moments of the Big Bang — Cosmologists work closely with Particle Physicists these days — but such energies cannot be achieved on Earth. Gigantic accelerators, like the LHC at CERN (in Switzerland and France[29] or the ill-fated SSC (Superconducting SuperCollider) in the USA, cost billions of dollars and take up thousands of square kilometers of space. Particle Physicists hope they will find the next "round" of new structure at these energies, but there are plausible theories that predict the next "interesting" break will come at stupendous energies far beyond those feasible on Earth.[30] If this is true, experimental Particle Physics may not end forever [we may one day build a synchrotron in orbit about the Sun] but the present socioeconomic structures will not be able to support further pushes toward higher energy. Particle Physics will then be forced to go back and take longer, harder looks at the particles already observed, and the "*Excelsior!*" school of Particle Physics will be at an end.

Still, it's been a great ride!

Physicists now are of the opinion that they are probably right, but the CERN LHC is still being built largely to make lots of t quarks to confirm its mass and other properties. Darn, I am getting ahead of myself again. Must be those pesky tachyons.

[26] There is now actual experimental evidence that there are *only six* quarks — or at least that any further quarks "generations" are so massive as to have no observable consequences in any experiments we might perform on Earth. If you want to know more about this story, ask a real Particle Physicist!

[27] The SUSY partner of the *photon* is the *photino*, the SUSY partner of the *graviton* is the *gravitino*, the SUSY partner of the $W^\pm$ *boson* is (I am not making this up!) the *wino*, and so on. This is not a joke, but no one knows if it is "real" either. That is, we do not yet know if Nature contains phenomena for which there is no other known explanation.

[28] My personal opinion is that such extravagant claims miss the point of Physics almost entirely. We know, for example, that the ordinary properties of solids are governed completely by $\mathcal{QED}$, the most perfectly understood physical theory in the history of Humanity, but we are still discovering unexpected qualitative behaviour of solids as we explore the seemingly endless variety of ways that large numbers of simple units (like electrons) can interact collectively with other simple units (like phonons or positive ions). To understand the components out of which things are built is *not* the same as understanding the things! So-called "naïve Reductionism" is alive and well in certain overly arrogant elementary particle Physicists. . . .

[29] The LHC is a *big* accelerator!

[30] Let me tell you about my design for an accelerator in geosynchronous orbit. . . .