The eighteen arbitrary parameters of the standard model in your everyday life

Robert N. Cahn

Physics Division, Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720

Contrary to popular conception, the purpose of particle physics is to understand the everyday world. The current theory of fundamental interactions among the quarks and leptons depends on eighteen parameters, which are *a priori* arbitrary. Were these parameters different, our world would be changed dramatically. By exploring the connection between these parameters and everyday phenomena we can better appreciate the challenges confronting contemporary particle physics. Until we can explain the origin of these parameters, we cannot say we truly understand why our everyday world is as it is. [S0034-6861(96)00203-6]

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I. A MUONIC WORLD

Every second, tens of cosmic-ray muons traverse your body,[1] leaving in their wake electron-ion pairs, disrupted molecules, and occasionally a mutated gene. When protons that have journeyed from outer space smack into nuclei in the atmosphere, muons rain down as debris, as calling cards from the other worlds that are the sources of the high-energy protons. Muons are messengers, too, from worlds that might have been.

We can imagine a world where electrons are as massive as muons, indeed are replaced by muons. There the muon would be absolutely stable, inheriting that characteristic as the lightest charged particle. Since the scale of atoms and thus of our material world is set by the Bohr radius, which is inversely proportional to the electron's mass, the distance scale in the muonic world would be 200 times smaller, while the energy scale would be 200 times greater. Imagine people shrunk in linear dimensions by a factor of 200, seeing "light" made of photons with energies of a good fraction of a keV. Minimuonic molecules would be rescaled versions of electronic molecules, with nearly static nuclei encircled by swift muons.

While the muon would be stable, atoms would not be. Ordinary muonic atoms—atoms with just one muon inside the electron cloud—are well studied. They survive until either the muon decays, in about 2 μsec, or until the muon is captured in the nucleus through the weak interaction

$$\mu^- + Z_A \rightarrow \nu_\mu + (Z-1)_A . \tag{1}$$

In the muonic world, since the muon would never decay, every atom would undergo muon capture. The simplest atom, hydrogen, would decay into a neutron and a neutrino. On the other hand, the neutron would be stable since its β decay into a proton, a muon, and an antineutrino would be energetically impossible.

Indeed, the universe would have emerged from the Big Bang made entirely of neutral particles, since all protons and muons would have disappeared into neutrons and neutrinos when the universe cooled below the temperature of 100 MeV, the energy needed to recreate protons and muons from the collisions of neutrons and neutrinos.

Nothing like this happened in our universe. Electron capture is rare in our world because if a proton tries to absorb an electron, there generally is not enough energy to make a neutron. This can occur only in favorable nuclei, like Be^7, where the nuclear energies conspire appropriately. In contrast, in the muonic world, muon capture would be mandatory. A peculiar universe it would be, made of just neutrons and neutrinos. No stars would shine, for the only stars would be neutron stars. The cosmos would be a giant billiard game with occasional spectacular, if invisible, collisions.

How close are we to this oblivion? What would happen if, starting from our present world, we gradually turned a dial that could tune the electron's mass from its

[1]The muon flux is about 1.5×10^2 m^{-2} s^{-1}. See, for example, The Review of Particle Properties (Montanet *et al.*, 1994) p. 1269.

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present value to that of the muon? As the mass increased, more and more atoms would undergo muon capture. On the other hand, some nuclei that had been unstable against β decay would become stable, as the electron became too massive for them to emit. At the same time, the linear dimensions of all atomic matter would shrink. When the mass of the electron, which began at 0.511 MeV, reached 0.668 MeV, N^{14} would start to disappear in favor of C^{14}. Continuing to turn the dial would cause the remaining atoms to disappear. As each nucleus absorbed muons, the excess of neutrons over protons would increase until the nucleus became too neutron rich and spewed off excess neutrons. Both free neutrons and free protons would be stable, but eventually every electron and proton would be transformed into a neutron and a neutrino. Of course, if the universe began with heavy electrons, all nucleosynthesis would be changed.

II. TODAY'S THEORY

It is a good thing no one can turn a dial for the electron mass, for its current setting is just fine. In today's theory of fundamental particles, however, there is such a dial. It is simply a dimensionless number that multiplies one term in the Lagrangian, the expression that gives the rules for calculating the predictions of the theory. In fact, the theory, as we understand it today, has eighteen dials. (A nineteenth is stuck near zero, and we do not discuss it further.) Nine of these set the masses of the quarks and charged leptons. Just a slight twist of a dial and the universe would be transformed.

These dozen and a half parameters appear to us now to be arbitrary, though there is widespread suspicion that this arbitrariness is an illusion, simply a reflection of our current ignorance. Despite the enormous success of the accepted theory, its incompleteness is apparent. We can stare at the eighteen dials, suspecting that behind them lie mechanisms that connect one to another. If we could twist one dial, we could watch to see if others turned as well, revealing the linkages. Alas, the dials are not ours to turn, and as long as we do not understand why the parameters have the values they do, our understanding of our physical environment will remain fundamentally incomplete: we shall be unable to explain at a fundamental level why there are even atoms and molecules.

We can succinctly summarize what is known about the fundamental particles. The tangible world is made of electrons, neutrons, and protons. We know that the last two are not elementary particles, but composites of the two lightest quarks, the u and d. Just as the u and d form a pair whose electric charges, +2/3 e and –1/3 e, respectively, differ by one unit, so too the electron has a partner, the electron-type neutrino ν_e, which is neutral. These four elementary entities, two quarks and two leptons, form a complete ensemble that can be described with marvelous precision by the theory that is now universally accepted by particle physicists.

TABLE I. Table of the quarks and leptons: The quarks are shown above and the leptons below. In the upper right-hand corner of each box is the electric charge, and in the lower right-hand corner is the mass in GeV. The three vertical columns indicate the three apparent generations.

u	2/3 0.005	c	2/3 1.5	t	2/3 175
d	–1/3 0.010	s	–1/3 0.15	b	–1/3 4.5
ν_e	0 0?	ν_μ	0 0?	ν_τ	0 0?
e	–1 0.0005	μ	–1 0.106	τ	–1 1.78

Inexplicably, Nature has handed us two more complete ensembles, each entirely analogous to the first, differing only in the values of the masses of the analogs of the electron and the u and d quarks. All the neutrinos are massless, or nearly so. The seemingly redundant copies of the electron are the muon μ and the tau lepton τ. The muon is joined by the muon-type neutrino ν_μ and the c and s quarks to make the second generation of elementary particles. The final generation is the τ lepton, its neutrino, and the t and b quarks. The three generations are shown in Table I.

The quarks and leptons interact in simple ways. The electromagnetic force is carried by the photon. When a photon is absorbed or emitted, the quark or lepton type is unchanged. The weak force that is transmitted by the W^+ or W^- boson does change the quark or lepton type, "the flavor," as it must to conserve electric charge. Nuclear β decay occurs when a d quark turns into a u quark and a virtual W^-. The virtual W^- then becomes an electron and an electron-type antineutrino. The weak force mediated by the Z boson, like the electromagnetic force, does not change the flavor of the interacting quark or lepton. The strong force, which is carried by gluons and does not influence leptons, never changes the quark flavor, but it can change another attribute of the quark, whimsically called "color." A u quark that absorbs a gluon remains a u quark, but its color may change among three alternatives, say "red," "blue," and "green." The gluonic interactions are called quantum chromodynamics (QCD), in a continuation of the wordplay.

Our knowledge of fundamental particles and interactions is such that we can explain everything about our everyday world and we can explain nothing at all. The current theory of particle interactions gives a set of very explicit rules for computing the forces between the various quarks and leptons.

Given the masses of the quarks and leptons, and nine other closely related quantities, that theory can account, in principle, for all the phenomena in our daily lives and, in fact, for all the data obtained from experiments at accelerator laboratories around the world.[2] On the other hand, we have no explanation of why there are three families of quarks and leptons, or why they have the masses they do.

III. IF THE PROTON WERE HEAVIER THAN THE NEUTRON

Except for their electrical charges, a proton and a neutron are quite similar. If you knew just that fact, you'd probably guess that a proton is heavier than a neutron, reasoning that there must be some extra Coulomb energy associated with the charge. Well, this reasoning is surely wrong since the neutron has a mass 1.3 MeV greater than that of the proton. The explanation is simply that in our world the dials are set so that the d quark is heavier than the u and the neutron has two d's and one u, while the proton has two u's and one d. The quark-mass difference overcomes the Coulomb-energy contribution. Most of the mass of the proton or neutron comes from the cloud of gluons attached to the quarks, as we discuss below, but this contribution is the same for the two. Turn up the mass of the u quark by 2.6 MeV and the proton would be heavier than the neutron by 1.3 MeV instead of the other way around.

The results would be disturbing to say the least. Suddenly hydrogen nuclei—protons—would start to decay, and positrons would be emitted. The positrons would encounter electrons and annihilate, giving off pairs of characteristic 0.511-MeV gammas. Of course many other nuclei would become unstable: there would be a general trend towards more neutron-rich nuclides. Tritium would be stable rather than He^3, Be^{10} not B^{10}, and C^{14} instead of N^{14}. The environment would be infested by an especially nasty pollutant: stable, thermal neutrons.

Of course this is not the right way to view a world with protons heavier than neutrons. We have to go back to the beginning, the real beginning. During the Big Bang, both the proton and neutron can be regarded as stable during the interval much earlier than 1000 seconds, the lifetime of the neutron, or, in our mass-reversed world, the lifetime of the proton. After one second, when the temperature is about 1 MeV, inverse β decay becomes too weak to keep neutrons and protons in equilibrium as the expansion decreases their density, and the lighter neutrons predominate over the protons by about 100 to 15 (see, for example, Clayton, 1983). The protons are mostly transformed by nuclear interactions to He^4, leaving the universe composed of about 25% helium by mass and nearly all the rest neutrons. Of course there would be traces of deuterium and tritium, the latter being stable against β decay. Subsequently, the few free protons left would decay. After further cooling, atoms would form, primarily of course helium. Roughly speaking, the universe would be much the same as ours at the same stage, except that every hydrogen atom would have been replaced by a neutron and a neutrino. The evolution of stars made from this primordial stuff would be quite rapid because the pp reaction, which fires stars initially, would instead be an nn reaction, without any Coulomb barrier. Indeed, ubiquitous neutrons would totally change nucleosynthesis.

IV. BASIC ISSUES BEFORE PARTICLE PHYSICS

These two alternative worlds—one with muon replacing the electron as the lightest charged lepton, and the other with the neutron lighter than the proton—show how dramatically different our world would be if some apparently arbitrary quantities—some particle masses—were magically changed. What determines these quantities, the masses, the number of charged leptons, and such?

These are among the basic questions that face particle physics today. Of course these questions have been with us since at least the time of the muon's discovery. What is new is that these questions have passed from the realm of metaphysics or philosophy to that of science. By this I mean that the questions are amenable to scientific examination, both theoretically and experimentally. Today, two terms, each with about 1000 scientists, are designing competing detectors that will measure collisions at CERN's Large Hadron Collider (LHC), which will be completed around the year 2004. Their goal is to address these simple and profound questions.

We take for granted so much of what surrounds us that we must take a step back to recognize what it is about the physical world that requires explanation. Our current description of physical laws has two components. The first is a set of rules for calculating the probabilities of various processes occurring. The second is a list of eighteen parameters, masses and such, that need to be inserted into the calculations at appropriate moments. Since these parameters have no explanation at present, they must be regarded as arbitrary. By modifying a parameter we obtain a perfectly good description of a world that might have been. By considering such alternatives, we see how much we really have to explain.

It is not just the masses that seem arbitrary in our picture. Why are there three columns of quarks and leptons? One would suffice for building a perfectly agreeable world. If there were only the first generation, the universe might be pretty much the same as it is today (though it might be virtually empty, as we mention below). If the one generation were made of the u and d quarks, together with the muon and its neutrino, or if the u quark were 2.6 MeV heavier, we would have the

[2]Some problems in particle astrophysics challenge the standard model of fundamental interactions. The number of neutrinos arriving from the sun appears to be too low. This could be due to oscillations between different types of neutrinos. Also, the mass of visible stars is too small to explain the gravitational forces on stars within our galaxy or the forces on galaxies themselves. This may indicate the existence of "dark matter," matter that is not located in visible stars. This matter might be due to massive neutrinos or to more exotic elementary particles.

bizarre world described above, a world eventually with nothing but neutral particles, neutrinos and neutrons.

V. IF THE SECOND GENERATION WERE THE FIRST

And what if the single generation consisted of the c and s quarks, the muon and its neutrino, a world with a single generation that is our second generation? Because the c quark is much heavier than the s, the stable baryons would be composed entirely of s quarks. This is totally unlike our world, where the neutron and proton have nearly the same mass because the u and d quarks have nearly the same mass. The particle made of three s quarks was discovered in 1964. It is called the omega-minus, Ω^-.

What kind of world could we build from omega minuses? The only possible nuclei would have one, two, or three omega minuses, and so on. Would two omega minuses bind? Nuclear forces are conveniently viewed as coming from the exchange of mesons. In our world, the pions play this role, as first suggested by Yukawa in 1935. The lightest mesons in the world with only c and s quarks would be made of an s quark and an anti-s-quark. Its mass would be about 1 GeV. Even if the force were attractive, with this large mass the potential might have a range too short to be binding. If that were the case, the second generation would make a world about as boring as the one composed just from neutrons and neutrinos: nothing but ersatz hydrogen, omega minuses encircled by positive muons.

VI. COUPLING STRENGTHS

Masses are not the only parameters whose values we must take as givens until we have a more complete theory. The interactions between the various quarks and leptons are governed by coupling constants, the best known of which is the electric charge e. In the units favored by high-energy physicists, the fine-structure constant is $\alpha_{\rm em}=e^2/4\pi$.

One of the most important insights of the past two decades is that these coupling constants are not constants at all. In a sense this has been known since the mid-thirties, when Uehling and Serber showed that around a static electric charge there is a cloud of virtual electron-positron pairs called vacuum polarization (Serber, 1935, Uehling, 1935). If the static charge is positive, the cloud around it is negative and shields it partially. Penetrating to short distances reveals a larger charge, so the potential is actually stronger than Coulombic at short distances. Short distances correspond to high momenta or high energy scales. Thus we see that $\alpha_{\rm em}$ ought to be regarded as a function $\alpha_{\rm em}(M)$ of the scale M at which it is measured. For example, while $\alpha_{\rm em}(0)\approx 1/137$, $\alpha_{\rm em}(m_Z)\approx 1/129$. The difference between these two values is a consequence of the vacuum polarization due to the quarks and charged leptons whose masses are less than the mass of the Z.

Vacuum polarization is a manifestation of the uncertainty principle. Although there is not enough energy available to produce electron-positron pairs, they appear as fluctuations of short duration. The phenomenon is universal. Quark-antiquark pairs are created as well. Indeed, every particle-antiparticle pair is constantly being created only to vanish again. These virtual events have real consequences, such as like modifying the Coulomb potential. While it is sometimes asserted that the W and Z particles first observed at CERN in 1983 (Arnison *et al.*, 1983) had not been present since the earliest moments of the universe, in a real sense they are always present and always being felt. Indeed, all the particles present in the Big Bang are recreated every instant through the uncertainty principle. The t quark may be hard to find at the Tevatron, but it is ubiquitous as a virtual particle, and with important consequences.

VII. UNIFICATION

It is an attractive possibility that the weak, strong, and electromagnetic forces are really unified, that is, are different manifestations of a single underlying force. We have already learned that the weak and electromagnetic forces are unified. For example, the Fermi constant of β decay, G_F, the fine-structure constant $\alpha_{\rm em}$, and the mass of the W and Z bosons are connected by the relation

$$\sqrt{2}G_F=\frac{\pi\alpha_{\rm em}}{m_W^2(1-m_W^2/m_Z^2)}, \tag{2}$$

which is quite accurate if $\alpha_{\rm em}(m_Z)$ is used in the numerator.

Grand unification would link electroweak interactions with strong interactions. Then at some short-distance scale (or high-energy scale) the two electroweak couplings and the coupling of strong interactions would become equal (except for some simple factor like 1/3). At longer distance scales (or smaller energies) these couplings are different: they evolve in predictable ways. From this point of view, it is absurd to try to derive $\alpha_{\rm em}(0)$ from some purported number of degrees of freedom of the electron, as suggested long ago by Eddington (Eddington, 1946), from purely geometrical considerations, or from requiring that quantum electrodynamics be a finite theory. From this perspective $\alpha_{\rm em}(0)$ is no more fundamental than $\alpha_{\rm em}(m_Z)$. The mystique of 1/137 is nothing but mystique.

If we fix $\alpha_{\rm em}$ at some high mass scale, we can calculate how it "evolves" to lower mass scales. This evolution is the result of vacuum polarization. Each charged fermion contributes to the evolution through

$$\frac{\partial\alpha_{\rm em}(M)}{\partial \ln M^2}=\frac{1}{3\pi}\,\alpha_{\rm em}^2 Q^2. \tag{3}$$

Here Q is the charge of some fermion light enough to contribute to the vacuum polarization at the mass scale M. For the t quark, Q=2/3, and we need to multiply by 3 since there are three colors of t quark. Thus, for $M\leqslant m_t$, the t quark contributes to the evolution of $\alpha_{\rm em}$ by

$$\frac{\partial 1/\alpha_{\rm em}(\bar{M})}{\partial \ln M^2}=-\frac{4}{9\pi}. \tag{4}$$

VIII. IF THE *t* QUARK HAD A MASS OF 17 GeV

The mass of the t or top quark is now known to be near 170 GeV (Abachi *et al.*, 1995; Abe *et al.*, 1995). Not so long ago, many of us would have guessed the answer might turn out to be around 17 GeV. Does this matter for our everyday world? If couplings are fixed at high mass scales and evolve to lower mass scales, reflecting the vagaries of quark masses, then the familiar fine-structure constant would be different if the t quark had turned out to be lighter, say α_{17}, rather than its actual value, which we can indicate by α_{170}. Simply integrating Eq. (4), we find

$$\frac{1}{\alpha_{17}(0)}-\frac{1}{\alpha_{170}(0)}=-\frac{4}{9\pi}\ln\left(\frac{17}{170}\right)^2=0.65. \tag{5}$$

Since α is about 1/130, this would be a 0.5% decrease in its value.

The strong-coupling constant α_s evolves in an analogous fashion. The appropriate equation is[3]

$$\frac{\partial 1/\alpha_s(M)}{\partial \ln M^2}=\frac{11-\frac{2}{3}n_f}{4\pi}. \tag{6}$$

Here n_f is the number of quark flavors ($u,d,s\ldots$) with masses below the scale M. What is the 11? It comes from the interaction of gluons with themselves. As long as there are 16 or fewer flavors, α_s decreases at high mass, a feature known in the jargon as "asymptotic freedom."

It is easy to solve this equation (since we have dropped the inconvenient, higher-order terms):

$$\alpha_s(M^2)=\frac{4\pi}{11-\frac{2}{3}n_f}\frac{1}{\ln(M^2/\Lambda^2)}, \tag{7}$$

where Λ is an integration constant that is determined once we know the value of α_s at some mass M. The value of α_s is known at the scale m_Z from measurements made in a great variety of experiments (Montanet *et al.*, 1994):

$$\alpha_s(M_Z^2)\approx 0.12. \tag{8}$$

At the scale m_Z all the quarks except the t are accessible, so n_f=5. From this we can infer that Λ_5 is about 200 MeV. The subscript 5 indicates that five flavors were considered. Above the t quark threshold we have n_f=6, and we must use Λ_6 instead. To guarantee that α_s is continuous at the scale m_t we need, from Eq. (7),

$$\left(\frac{m_t^2}{\Lambda_5^2}\right)^{11-(2\times 5)/3}=\left(\frac{m_t^2}{\Lambda_6^2}\right)^{11-(2\times 6)/3}. \tag{9}$$

Similar conditions connect the values of Λ_3, Λ_4, Λ_5, and Λ_6. The u, d, and s quarks are quite light, with masses of roughly 5 MeV, 10 MeV, and 150 MeV, respectively. Thus inside the proton it is Λ_3 that is appropriate. Indeed since the proton is made of u and d quarks, whose masses are much smaller than Λ_3, the only possible scale for the proton's mass is Λ_3:

$$m_p=C\Lambda_3, \tag{10}$$

where C is a constant that can be, in principle, calculated nonperturbatively, say by Monte Carlo simulation of QCD.

The spirit of grand unification requires that it be α_s at very large masses that is fundamental. The value of Λ_3 reflects the values of the c, b, and t quark masses. In particular,

$$\Lambda_3^2\propto(m_t^2)^{2/27}, \tag{11}$$

so if the t quark's mass were 17 GeV instead of 170 GeV, the proton's mass would be less by a factor $(1/10)^{2/27}$=0.84, if the grand unification hypothesis is correct. The evolution of the strong-coupling constant for m_t=170 GeV and m_t=17 GeV is shown in Fig. 1.

So far, there is no direct experimental evidence for grand unification. Nonetheless, the idea is certainly attractive. In addition, there is some very circumstantial evidence in support of the proposition. We can take the observed values of the couplings of gluons (α_s), of photons ($\alpha_{\rm em}$), and of W's ($\alpha_{\rm weak}$) and extrapolate them to very high mass scales to see whether they are equal. This extrapolation depends on the particles whose masses lie between the low energy scale and the very high scale at which unification might occur (typically 10^{15} GeV or so). Using the most basic models, the answer is it doesn't work. However, a fancier alternative, popular for reasons we describe later, works astonishingly well.

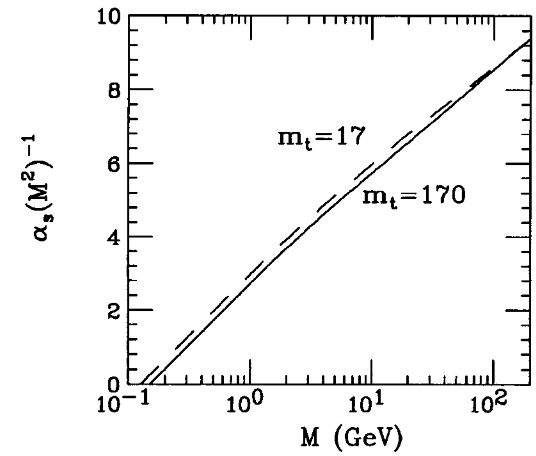

FIG. 1. The evolution of the reciprocal of the strong coupling $\alpha_s(M^2)$ as a function of the mass scale M^2 shown both for our world (m_t=170 GeV, solid line) and an alternative world (m_t=17 GeV, dashed line): The alternative world has smaller values of the coupling and thus smaller values of the parameter Λ. In the alternative world, the proton would be lighter by a factor of 0.84.

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[3]A useful and concise discussion appears in (Montanet *et al.*, 1994). See, in particular, pp. 1297–8.

IX. WEAK DECAYS

We have mentioned 12 free parameters: the masses of the six quarks and the three charged leptons and three coupling constants. There are six more, four of which are related to β decay.

Beta decay is universal. A charge 2/3 quark can turn into a charge –1/3 quark by emitting a W^+, which can turn into a lepton-antilepton pair or a quark-antiquark pair. Thus we observe charm decays of the sort $c \rightarrow s\mu^+\nu_\mu$, $c \rightarrow su\bar{d}$. Although the c quark can turn into either an s or a d by emitting a W^+, it chooses the former much more often than the latter.

The predilection of quarks to decay into other quarks in the same column (see Table I) or, if that is not possible, to the next column is quantified in 3×3 matrix V,

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}. \tag{12}$$

For example, the amplitude for decay of a b quark into a u has a factor V_{ub} in it. This matrix arises because the states the weak interactions see as fundamental and the mass eigenstates are not exactly the same. The matrix V, called the Kobayashi-Maskawa (KM) matrix (Kobayashi and Maskawa, 1973), represents the effect of rotating from the weak-interaction basis to the mass eigenstate basis. It follows that the matrix V is unitary. While a 3×3 unitary matrix has nine free parameters, it is not too hard to show that only four of these are physically significant. The others are simply a matter of phase convention.[4]

How do these four parameters influence our lives? It may be that one of them is responsible for our being here. If V were real, it would be simply a 3×3 rotation matrix, and it could be parametrized by three Euler angles. The fourth free parameter makes it truly complex. As Kobayashi and Maskawa pointed out, this means that CP is violated in the weak decays. The violation of CP, the combination of charge conjugation and parity invariances, was discovered in 1964 (Christenson *et al.*, 1964). It seemed at first to lack a connection to other parts of physics, but in 1967 Andrei Sakharov (Sakharov, 1967) showed that if we are to explain the baryon-antibaryon asymmetry of the universe, we need CP violation. We do not know that the CP violation thus required is, in fact, furnished by the KM matrix. If it turns out that it is furnished by the KM matrix, we shall know that we are here only because there are three generations, for with only one or two generations the KM matrix cannot provide CP violation. There may be sources of CP violation besides the KM matrix, but to understand CP violation this is where we must start. This is the goal of the B factory at SLAC and of the analogous machine at KEK in Tsukuba, Japan, both of which are under construction.

X. ELECTROWEAK SYMMETRY

The final two parameters that specify the current theory of fundamental interactions are the least understood. They address the breaking of electroweak symmetry. Particle physics has developed through a tension between symmetry and symmetry breaking. First we uncover an approximate symmetry, then we try to learn why it fails to be a true symmetry. Isospin is an approximate symmetry, first recognized as the similarity between the neutron and proton, which form an isodoublet. The symmetry is not exact. The proton and neutron masses are very similar but not identical. Clearly the symmetry is broken by electromagnetic forces, which influence the proton and neutron quite differently. We now understand that isospin symmetry is also broken by the difference in mass between the u quark and the d quark, a difference that is not the result of electromagnetism.

The contemporary theory of electroweak interactions is based on a symmetry similar to isospin. The left-handed (spin antiparallel to the direction of motion) u quark and the left-handed d quark form a "weak isodoublet," as do the left-handed electron and neutrino. Only the left-handed pieces are considered because these are the parts that interact with W bosons: In β decay, the emitted electrons are left handed (in the limit in which the electrons are ultrarelativistic). Certainly this symmetry is broken, since the electron and neutrino are quite dissimilar. Indeed, if it were not broken, all the quarks and leptons, and the W and Z, too, would be massless.

Usually a symmetry can be broken by introducing an interaction that directly contradicts the symmetry. A magnetic field along the z direction will break the spherical symmetry of the hydrogen atom and introduce energy differences between states with differing values of l_z and s_z that would otherwise be degenerate. It turns out that this kind of bias cannot be introduced for the electroweak interactions. Explicit symmetry breaking destroys the theory altogether, rendering it incapable of making any predictions. The symmetry must be broken, but without biasing the result from the outset. The theory must break its own symmetry, a process called spontaneous symmetry breaking.

Ferromagnetism is a useful analogy. The interaction between the spins of electrons i and j in a ferromagnet is made up of terms like $\sigma_i \cdot \sigma_j$. No special spatial direction is singled out. Nonetheless, within a domain, the spins that participate line up in a single direction to produce a magnetization M. In order to decrease the energy of the ferromagnet, below the Néel temperature, the magnet must choose a direction, any direction, in which to point.

To break the electroweak symmetry something must pick a direction in the "internal" symmetry space. One

[4]We have assumed throughout that the neutrinos are massless. If they are massive, there is a KM matrix for the neutrinos and seven new parameters, three for the masses and four for the new KM matrix. The masses and mixing angles could be found by observing oscillations of neutrinos from one species into another. This is an active field of experimentation.

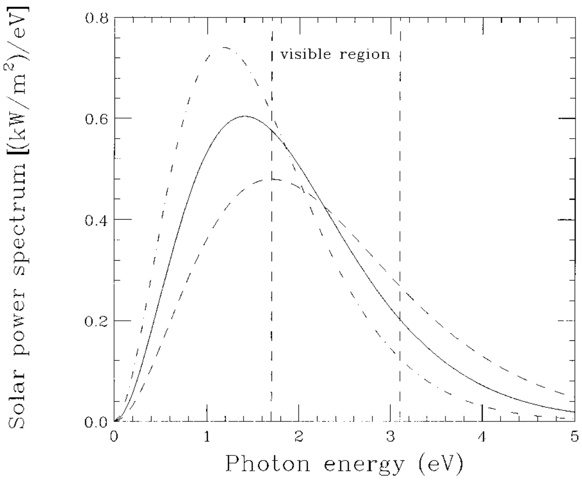

FIG. 2. Solar power spectrum incident on the Earth [(kW/m^2)/eV]: Solid curve, actual spectrum, surface temperature 5800 K; dot-dashed curve, W mass one-half of actual value, giving a surface temperature 4800 K, a luminosity 1.025 times actual, and a radius 1.45 times actual; dashed curve, W mass twice actual value, giving a surface temperature 7000 K, a luminosity 0.96 times actual, and a radius 0.67 times the actual radius. The visible region from 1.7 eV (λ=792 nm) to 3.1 eV (λ=400 nm) is indicated. The calculations and curves were provided by J. D. Jackson (Jackson, 1995).

way to do this is to introduce a scalar field ϕ with several components, roughly analogous to the spatial components of M. The field ϕ then serves as a sort of compass. One component of ϕ takes on a nonzero value everywhere in space, just as a component of M does. The magnitude v that ϕ takes on is simply related to the Fermi constant:

$$\sqrt{2}G_F=\frac{1}{v^2}, \tag{13}$$

which means that v=246 GeV.

In the simplest model of spontaneous symmetry breaking, ϕ has four components, each representing a physical degree of freedom. Before the symmetry breaking, the photon, the W^+, the W^-, and the Z are all massless, with two independent polarizations, just as the photon still has. After symmetry breaking, the W^+, the W^-, and the Z are massive states with three independent polarizations. Where do the extra degrees of freedom come from? They come from ϕ. This still leaves one degree of freedom, one new particle, which is called the Higgs boson. Nothing we have done can tell us what the mass of this Higgs boson should be.

The values of v and the mass of the Higgs boson are the final two parameters of the standard model. How would the observable world change if we modified them? The Fermi constant, which governs the rate of weak interactions, is inversely proportional to v^2. There is a single weak-interaction process whose occurrence is essential to our everyday lives, the fusion $pp\rightarrow de^+\nu$. This begins the pp cycle, which fuels the sun. Increasing v a bit would slow the fusion reaction. This, in turn, would cause a contraction of the sun and a consequent increase in the temperature until its original luminosity was just about regained. Nonetheless, changes would be apparent.

If v were doubled, doubling the mass of the W and reducing the Fermi constant by a factor of 4, the sun's radius would shrink by 33% (Jackson, 1995). Since the luminosity would not be changed much, the temperature at the sun's surface would have to increase to emit the energy at the same rate. Since the radiation varies as T^4 while the surface area varies as R^2, the temperature would increase by about 22%. The sun would appear smaller and brighter. The consequences would not be just esthetic. The increased temperature would shift the visible light toward the ultraviolet, as shown in Fig. 2. This might have affected the evolution of green plants and would, in our cancer-conscious world, boost the sales of sun-blocking skin lotions.

The weak interaction in the pp process turns a u

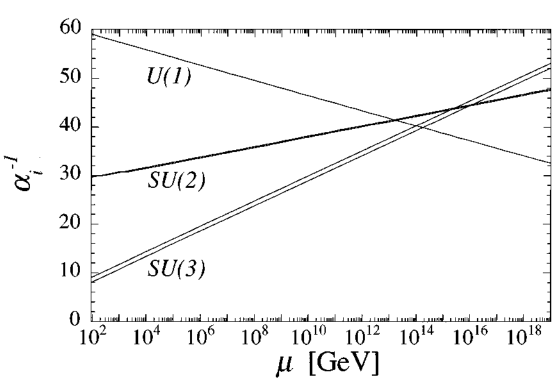

FIG. 3. The evolution of the couplings of the standard model without supersymmetry. The electromagnetic and weak couplings are combinations of U(1) and SU(2). The strong coupling is denoted SU(3). If the interactions arise from a single grand unified force, the three couplings should come together at a single point. The figure was provided by H. Murayama (private communication).

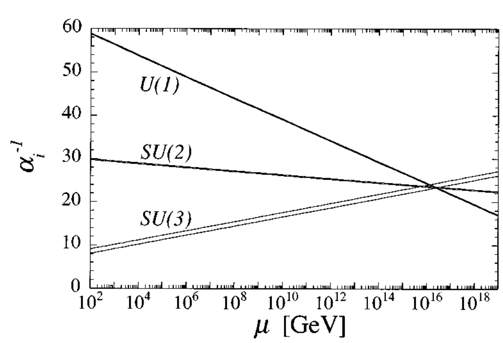

FIG. 4. The evolution of the couplings of the standard model with supersymmetry: Because the supersymmetric world has extra particles, the evolution of the couplings is different from those in the nonsupersymmetric world. In the supersymmetric model the couplings converge at a single point, suggesting there is unification of the electroweak and strong interactions. The figure was provided by H. Murayama (private communication).

quark into a d quark, and thus the amplitude includes a factor V_{ud}. While this element of the Kobayashi-Maskawa matrix is close to unity, it need not have been. If it were dramatically different from one, it too, like the value of v, would change the characteristics of the sun.

What about the mass of the Higgs boson? It turns out that there is a conspiracy that hides the value of the Higgs mass from view. It enters only feebly into observable quantities. It is partially for this reason that we have little idea what the mass of the Higgs boson is. The more important reason is that we do not even know that there is a single Higgs boson. There may be several. There may be none.

XI. SUPERSYMMETRY

Supersymmetry audaciously insists that for every fundamental particle we have mentioned above there is another related particle whose spin differs from it by half a unit. For the electron there is a spin-zero selectron, for a quark, a spin-zero squark, for the W, Z, and photon a spin-one-half wino, zino, and photino. In addition, supersymmetry requires that there be a multitude of Higgs bosons, three neutral ones and two charged ones, at the very least. None of these bizarre supersymmetric entities has as yet shown itself, but the search continues at Fermilab's Tevatron and at CERN's electron-positron collider, LEP. Supersymmetry will be a prime target for the LHC. One reason this theory is so popular is that, when all these extra particles are included and the coupling constants measured at low energies are extrapolated back to high energies, the three values intersect at a single point, the essential prediction of grand unification, as shown in Figs. 3 and 4.

If we suppose that the world possesses supersymmetry, we are invited to ponder what would have happened had the selectron been lighter than the electron, and the squarks lighter than the quarks. In other words, what would the world be like if the tangible world were made of bosons. Despite the public's fascination with the uncertainty principle, the aspect of quantum physics with the most pervasive influence must be the exclusion principle. The structure of atoms follows from the Aufbau procedure; chemistry is a consequence of the variety of electron configurations. But the significance of the exclusion principle, the importance of being fermi, is greater even than this suggests.

If we had selectrons in place of electrons, every selectron in an atom would find its way into the lowest-level s-wave state, a sort of mini-Bose condensation, and atoms would be much smaller than predicted by the Fermi-Thomas model. The more profound change would be that molecules would have no integrity. There is chemistry not solely because some atoms combine to form molecules and some molecules react to make new molecules, but because some atoms do not combine and some molecules do not react. The repulsion between atoms is simply the reflection of the unavailability of orbitals with lower energy than the orbitals of the separate atoms. With bosons, though, there is always room in an energy-saving, if multiply-occupied, accommodation.

The consequences of transforming electrons and nucleons from fermions to bosons would be devastating, something like Ice-Nine in Kurt Vonnegut's *Cat's Cradle* (Vonnegut, 1963), only worse. All molecules would fuse into a single, undifferentiated blob, which itself would shrink inexorably. Ordinary matter made up of N atoms has an energy of order $-N$. The negative sign simply reflects the fact that the binding energy is negative. If we combine two chunks of matter, each having N atoms, we get an energy $-2N$. It does not matter whether the two lumps are separate or stuck together. In the world of bosonic electrons, the energy of N atoms varies roughly as $-N^{7/5}$ (Dyson, 1967; Lieb, 1990). Two separate lumps have an energy $-2N^{7/5}$, but if we stick the lumps together, their energy is $-(2N)^{7/5}$, which is much less. This means that all lumps coalesce. Indeed, two lumps coalesced would be smaller than either lump was before.

However attractive supersymmetry may be to the theoretical physics community, in it lurks the potential for catastrophe. We must be grateful—if supersymmetry there is—that the breaking of this symmetry left us with light, charged fermions, rather than light, charged bosons.

XII. QUESTIONS

There is a special pleasure that comes from identifying symmetries in nature, from understanding that the ubiquitous and tangible electron is an immediate relative of the elusive neutrino. But the challenge of particle physics today is to understand symmetry breaking, for that is what makes the world what it is. The neutrino and the electron are really as different as they can be. How does that happen? Why do we have two very light quarks and one very light charged lepton? Why did electroweak symmetry breaking leave one symmetry unbroken, bequeathing us the photon? Why is there light, and why does matter take the form it does? These are the goals of particle physics: not to describe the collisions of highly relativistic protons, but to learn why our world has the shape and form it does. But to answer questions about the everyday world we need to observe phenomena that occur only at very high energies.

Particle physics opens us to possibilities beyond the imaginings of science fiction: worlds composed entirely of neutrons and neutrinos; worlds with atoms composed of omega minuses and positive muons. These are alternatives that are *a priori* plausible, given our current understanding of fundamental particles and interactions. Most of these alternatives lack the possibility for the rich chemical structure of our world: they are terminally boring. We may not have "*le meilleur monde possible*," as Voltaire's Pangloss would have it, but it is a lot better than it might have been. But what actually determines the nature of the world around us? What sets the parameters that dictate that hydrogen exists, stabilized by the delicate balance that makes it lighter than a neutron? What fixed the breaking of the grand unified symmetry—supposing there is one—and left us with a powerful strong interaction rather than another weak one?

That the *u* quark is slightly lighter than the *d* quark gives us a stable proton. That the electron's mass is less than the mass difference between the neutron and proton guarantees that the hydrogen atom is stable against electron capture. The alternative worlds that would have been produced by the second generation's replacing the first are unimaginably different. Collectively, the eighteen arbitrary parameters of the standard model are the recipe out of which the universe is made. They dictate not just the microworld but the quotidian world. Particle physicists construct accelerators kilometers in circumference and detectors the size of basketball pavilions not ultimately to find the *t* quark or the Higgs boson, but because that is the only way to learn why our everyday world is the way it is.

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