Introduction to High Energy Physics

Paul Langacker

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Abstract

Introductory lecture on high energy physics, emphasizing the major goals and issues.

1 How does nature work at a fundamental level?

The description of any physical system requires three ingredients: (1) What are the basic entities to be described? (2) What are the forces or influences acting on them? (3) What are the rules of the game, e.g., how do the entities respond to those influences? For example, Newtonian gravity involves entities such as the Sun, Moon, Earth, apples, or people. The force is gravity, $\vec{F} = G_N m_1 m_2 \hat{r}/r^2$, and the response is given by Newton's laws, especially $\vec{F} = m\vec{a}$. In general relativity, space-time is added to the list of entities, which is distorted by matter, while point masses respond by following geodesics.

The essence of high energy (particle) physics is the description of nature at the most fundamental level. At our present level of understanding, the basic entities are elementary particles such as electrons, quarks, and photons. They interact by such forces as the strong (nuclear) force and electromagnetism. The framework is that of relativistic quantum field theory, which is the union of quantum mechanics, special relativity, and the possibility of particle creation or annihilation (such as the reaction $e^+e^- \to p\bar{p}$ via an intermediate virtual photon). Our understanding of these issues may eventually be supplanted by something more basic, just as Newtonian gravity was superseded by general relativity.

There is another issue that is often ignored or taken for granted: are the laws of nature absolute? That is, are they uniquely determined, perhaps by some underlying selection principle or by self-consistency, and are they the same everywhere in space-time? That is the implicit assumption of most physicists, and in fact we have not seen any conclusive empirical evidence to the contrary.

However, it is conceivable that the laws are at least to some extent arbitrary. Perhaps, they vary depending on the location in some vast multiverse, of which our observable Universe (some 14 billion light years in size) is just a small part. Similarly, the "constants" of nature, such as the fine struction constant $\alpha \sim 1/137$, might not be absolutely constant, but could instead vary with time or location even within our observable Universe. Or the observed laws might be just one component of some wave function of nature.

In fact, superstring theory appears to have an enormous *landscape* of possible vacua, each predicting different physics[1]. At our present level of understanding there is no selection principle to single out any one of these, so conceivably our physics is to some extent accidental. An analogy would be the average distances of the planets from the Sun. Johannes Kepler devoted a lot of attention to trying to understanding the planetary spacings in terms of absolute geometric principles involving the nesting of solids within each other. We now understand, however, that many stars have planets, and their locations are dependent on the details of the formation of the stellar systems and vary from star to star. Furthermore, some versions of *eternal inflation* suggest that new domains of a multiverse may be continually created, and that they may sample different parts of this string landscape. These two ideas together suggest the (highly controversial) possibility that the nature we observe may involve some element of *environmental selection* (a.k.a. the *anthropic* principle), i.e., that most regions of the multiverse may not be suitable for life. For example, they may collapse under gravity in $\sim 10^{-44}$ s, or conversely they may expand so rapidly that nothing like stars or galaxies can form. In that case, we can only live in those regions in which the local physics *is* suitable, just as life can only evolve on those planets with suitable conditions.

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[1] Superstring theory assumes the validity of quantum mechanics and relativity. It is conceivable that even these concepts are not unique.

2 The fundamental particles and interactions

Whether or not the laws are unique, the nature that we observe seems to involve a variety of point-like particles (quarks and leptons). By point-like, we mean that no evidence has been observed for a nonzero size, or that the quarks and leptons are composites of still smaller objects or of a continuous distribution of matter[2]. There are also at least four types of interactions[3] (strong, electromagnetic, weak, and gravitational), with very different properties. For example, the strong and weak interactions have very short ranges, while electromagnetism and gravity are long range. Or, the strong, electromagnetic, and gravitational interactions are reflection invariant (act the same way as their mirror images), while the weak interactions are not.

It is interesting to consider what essential roles are played by this variety of interactions and particles. This is clearly important if nature is not unique and some form of environmental selection is involved. If nature *is* unique, one can still examine the question of whether something as complex as life could have existed if the rules had been a little different. In fact, each of the known interactions does appear to be "essential" for life, in the sense that perturbing around our physics by simply eliminating any one of them would have catastropic consequences[4]. Gravity is necessary to "bring things together" into galaxies, stars, planets, etc., so that something can happen in a sparse universe[5]. Similarly, a variety of types of atoms and molecules (or something analogous) are needed for chemistry, materials, and life as we know it. Their existence and associated chemical reactions require loosely bound electrons and electromagnetism, or something similar. A variety of

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[2] Previous levels of compositeness, e.g., that atoms consist of electrons and nuclei, nuclei are bound states of protons and neutrons, and nucleons are bound states of quarks, have all involved weak coupling. For example, the binding energies of atoms or nuclei are small compared to the masses of the constitutents. Any further layers of structure for the quarks and leptons, on the other hand, would have to be very different: experimental searches indicate that the constituents would have to be very much heavier than the bound states and therefore have enormous binding energies. The quarks and leptons are not truly pointlike in superstring theory either, but there the situation is somewhat different: they are the massless modes of extremely tiny fundamental one-dimensional vibrating strings.

[3] The term interaction is more appropriate than force, in part because interactions can describe particle creation, annihilation, or transitions from one type of particle to another.

[4] It is possible and even very likely that alternative scenarios could be equally viable, but a systematic study is probably beyond our capabilities.

[5] There are implicit assumptions here, e.g., concerning the average density of the present universe.

atoms also requires a variety of nuclei, which is accomplished in our nature by starting with only two kinds of stable or quasi-stable nucleons (or quarks), which are held together in various numbers and arrangements by the strong interaction. The strong interaction is also needed for energy generation in stars, which prevents stellar collapse and is ultimately reponsible for most of our energy needs. Thus, gravity, electromagnetism, and the strong interactions hold things together, while chemical and nuclear reactions involve rearrangements of electrons or nucleons, respectively. The weak interactions do not hold anything together. Rather, they drive transitions such as β decay, $n \to pe^- \bar{\nu}_e$. Why is such nuclear alchemy essential? Unlike the other interactions, the essential role of the weak interaction involves the evolution of our world, not its static properties. Our present universe apparently evolved from a fairly uniform hot plasma, which at one time consisted mainly of protons, neutrons, electrons, positrons, neutrinos, and photons. The formation of elements heavier than hydrogen (known as *nucleosynthesis*) occurred in the early universe (mainly for ^{4}He), stars (elements up to ^{56}Fe), and in in core-collapse supernovae (for still heavier unstable elements), and involved reaction chains in which the weak interactions were essential.

Each of the known interactions therefore plays an essential role in the creation and existence of complex structures and life in our version of nature, though it should be reiterated that no claim has been made for the uniqueness of this set of interactions. What about the fundamental (point-like) particles? The two lightest types of quarks (the u and d, which are the main constitutents of the proton, neutron and pions) as well as the electron and its associated neutrino, all have essential functions in the scenario described above. In fact, these particles (known as a family or generation) are all that are needed for matter under ordinary terrestrial conditions. However, in extreme conditions, such as associated with cosmic rays and their interactions, or at high energy particle accelerators, we observe two heavier generations, which appear to differ from the first only in their larger masses and because of their kinematically allowed decay modes. We are still ignorant of why nature, or at least our local version, has these extra families.

Furthermore, for each fundamental spin-1/2 particle there exists in nature an antiparticle with the same mass but opposite values for such conserved charges as electric charge and baryon number (it is not known whether the neutrinos have a conserved charged, so it is possible that they are their own antiparticles). This is much better understood than the existence of heavy families: it is required by the union of quantum mechanics and relativity, as first became apparent from the antiparticle solutions to the Dirac equation[6]. The existence of these antiparticles allows for the creation or annihilation of particle-antiparticle pairs, such as their annihilation into two photons or into one virtual photon. Similar statements apply to bosons carrying nonzero charges. Particles and antiparticles have the same masses and lifetimes, and almost identical interactions. Actually, the weak interactions do distinguish between particles and antiparticles (C, or charge conjugation noninvariance). They also distinguish between a physical process and its mirror image (parity or space reflection noninvariance, P), but they are almost exactly CP invariant (e.g., an electron with its spin antiparallel to its momentum has weak interactions equivalent to those of a positron with its spin parallel). However, in the early 1960s it was observed that there is also a tiny ($\sim$ one part in 10^3) violation of CP, first observed in the decays of neutral K mesons. This came as a shock to the physics community at the time, but perhaps it should not be so surprising: quantum mechanics involves complex numbers, and CP violation typically occurs when a process involves two or more interfering amplitudes with different phases[7]. In our standard model of particle physics, there is no way to introduce an observable phase associated with the strong or electromagnetic interaction, but complex phases can be introduced in the interactions of the spin-0 Higgs field with the elementary fermions, leading ultimately to CP violation in the weak interactions. In fact, if there were only one or two fermion families, these would not be observable because one could redefine the phases of the fermion fields to eliminate them, but for three families there is an observable phase. This perhaps provides a glimmer of light on why there are three families, or at least pushes the question back a step to whether CP violation is necessary in nature. Indeed, there is a fairly compelling argument here, associated with the observed baryon (i.e., matter) asymmetry of the universe, i.e., our world is made predominantly of matter and not antimatter[8]. If the hot plasma of the early universe had in-

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[6] Dirac initially attempted to identify the positive charge solution of the electron equation with the proton, but it soon became clear that the two solutions must have the same mass.

[7] No violation has been observed for the combination CPT, where T represents time reversal. CPT invariance is a necessary consequence of any local, Poincaré invariant, unitary field theory.

[8] This holds for essentially the entire observable universe: if there were antimatter stars or galaxies out there, we would have observed the high energy gamma rays from annihilation with the small amounts of matter present in interstellar or intergalactic regions.

volved equal amounts of matter and antimatter they would eventually have annihilated efficiently, leaving only a tiny fraction of the amount of matter (relative to photons) that we observe and probably not enough for life. There must therefore have been an excess of around one part in 10^9 of particles with respect to antiparticles before they annihilated, most likely created by physical processes involving CP violation (amongst other ingredients)[9]. The observed CP violation in the weak interactions is not sufficient for this, but other related CP breaking in higher energy physics could be responsible.

3 Three eras

It is interesting to comment on three eras in the development of our understanding of particle physics, which I refer to as the *era of exploration*, the *standard model era*, and the *beyond the standard model era.*

3.1 Particle physics ca 1968

The era of exploration refers to the development of particle physics prior to the standard model. There are no rigid beginning or ending dates, but the period spans roughly from the publication of the Dirac equation in 1928 to the development of the electroweak $SU(2) \times U(1)$ model (late 1960's) or the development of QCD (early 1970's).

I will take 1968 as a somewhat arbitrary date for the end of the pre-standard model era. At that time there was a satisfactory theory only of electromagnetism (*quantum electrodynamics* or QED). Large numbers of strongly interacting particles (*hadrons*) had been discovered. Much was known empirically about their properties and interactions, including their symmetries and conservation laws (isospin, the eightfold way, strangeness, etc.), and it was known that the quark model gave a reasonable classification of many of the states. There were various phenomenological models of the strong interactions, but no successful quantitative theory. For example, although the

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[9] The excess could conceivably have been due instead to an initial condition on the big bang. However, if the universe underwent a brief extremely rapid period of inflation to smooth it out (as most cosmologists think is likely) then the initial matter and antimatter densities would have been diluted to essentially zero. The plasma that eventually condensed to form our structures would have been formed after a period of reheating, again requiring the asymmetry to have been generated by CP-violating processes.

Yukawa model of meson exchange gave an approximate description of the nuclear force in a certain limit, the field theory of pions and nucleons involved strong coupling and was not very successful. Other models focused on other aspects, e.g., *Regge theory* for high-energy scattering, or the more general *S-matrix theory*, which emphasized general principles such as the analyticity, unitarity, and crossing properties of scattering amplitudes[10]. Similarly, much was known empirically about the weak interaction decays. There was a field-theoretic model (the *Fermi theory*) that worked well at lowest order, but it was known to be inconsistent at high energies. Already by 1968 most of the ingredients of what would become the standard electroweak model had been formulated, but they were not yet widely accepted or understood. Finally, it was known that classical general relativity was very successful for gravity, but there was no quantum-mechanical version.

It should be emphasized that most of the semi-successful 1960's-era models for the strong and weak interactions are still valid as approximations or useful as phenomenological models in appropriate limits.

3.2 The standard model

The standard model of the strong, weak, and electromagnetic interactions was developed and (to a considerable extent) established in the late 1960's and the 1970's, though it incorporated many elements and first steps that had been proposed earlier.

A key ingredient was that of Yang-Mills (gauge) theory, first proposed in 1954, in which interactions are mediated by the exchange of (apparently massless) spin-1 gauge particles. Yang-Mills theories generalize QED, but allow elementary self-interactions of the gauge bosons. The electroweak part of the standard model, proposed in 1967, combines the Yang-Mills interactions with QED, the Fermi theory, and its *intermediate vector boson* extension (in which the weak interactions are mediated by the exchange of massive charged spin-1 particles called the $W^{\pm}$). The gauge interactions are associated with the $SU(2) \times U(1)$ group. The weak interaction gauge bosons (and chiral fermions) are given mass by the *Higgs mechanism* (through their interactions with a background spin-0 field), which spontaneously breaks the

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[10] One class of models based on S matrix theory, the dual-resonance models, were eventually reformulated as string theories for the strong interactions, and later reinterpreted as string theories for all interactions including gravity.

gauge symmetry but was postulated to preserve renormalizability. The specific Higgs mechanism for spontaneous symmetry breaking is the only major aspect of the electroweak model that is still unverified. The renormalizability of the model was proved a few years later. Weinberg's original 1967 model was for leptons only, because the natural extension to quarks utilizing just the three types that were then known (the u, d, and s) led to predictions for the neutral kaons that were inconsistent with experiment. This could be remedied by postulating a fourth (charm or c) quark (the *GIM mechanism*), and in fact the c quark was discovered with roughly the predicted mass a few years later. In addition to the charged current weak interactions mediated by the $W^{\pm}$ (responsible for weak decays), the $SU(2) \times U(1)$ model predicted a new *weak neutral current* interaction (WNC) mediated by a new massive neutral spin-1 particle, the Z boson. These neutral current interactions were subsequently observed. In the following decades the W and Z were observed with the predicted masses, and the WNC interactions and the properties of the W and Z were measured to high precision, in excellent agreeement with the theoretical predictions. The $SU(2) \times U(1)$ model with only two fermion families does not have any observable (CP-violating) phases, but as mentioned above the extension to three families does allow CP-violation. The third family particles were eventually observed, and many observations of CP-violation in the K and B meson sector (but not the baryon asymmetry) are consistent with this origin. The original electroweak model (like the Fermi theory) assumed that the neutrinos are exactly massless. However, by 1998 it was established that the neutrinos have tiny masses, solving the *Solar neutrino problem* (the observed deficit of ν_e from the Sun) by conversion of most of the ν_e into other types. The properties of the neutrino masses and mixings (e.g., whether the masses violate lepton number conservation) continue to be actively studied.

The strong interaction part of the standard model, Quantum Chromodynamics (QCD), was developed in the early 1970's. It was strongly motivated by the deep inelastic electron scattering experiments at the Stanford Linear Accelerator Center (SLAC), which indicated that the proton and neutron consist of pointlike constituents which interact relatively weakly at high energies. The kinematic distributions indicated that these constituents were spin-1/2, tying in nicely with the quark model that had been developed earlier to describe hadron spectroscopy. The quark model, including the color quantum number, was combined with $SU(3)$ Yang-Mills theory to give QCD. QCD also led to a simple understanding of the observed strong interaction flavor symmetries such as isospin, flavor $SU(3)$, and their chiral extensions. QCD was subsequently verified by experiments such as e^+e^- annihilation into hadrons and studies of heavy quark spectroscopy, which observed the effects of the gluon, the color quantum number, hadronic jets, and the running of the strong gauge coupling. Lattice calculations eventually allowed even more detailed tests of the low energy consequences of QCD.

The standard model combines QCD, the electroweak theory (generalized to include neutrino mass), and classical general relativity. It is a mathematically consistent description of nature. Most aspects have been verified, often to high precision, and (with the possible exception of the Higgs mechanism for spontaneous symmetry breaking) it is almost certainly valid down to distance scales around 1/1000th the size of the atomic nucleus. However, the standard model is incomplete. For example, it does not incorporate the observed cosmological dark matter and dark energy. Moreover, it has a number of theoretical complications which strongly suggest that it is not the ultimate theory of nature.

3.3 Beyond the standard model

The standard model has been extremely successful, far more so than could have been anticipated in 1968. Nevertheless, it is almost certainly not the final story. In particular, it is very complicated and has many (nearly 30) free parameters, such as the masses of the fermions and their mixings (observed in weak interaction processes). It also requires several severe fine tunings, including the Higgs mass, the cosmological constant, and the strong CP parameter, which can generate an electric dipole moment for the neutron. It also does does not include a natural unification with or quantum version of gravity.

There are many theoretical ideas for embedding the standard model in a more complete and fundamental theory. One important idea is that of unification, i.e., that two or more apparently distinct interactions are really just different aspects of a more fundamental one. A familiar example is the unification of electric and magnetic forces, which were once thought to be two different things, as two aspects of the electromagnetic interaction. Similarly, the electroweak part of the standard model at least partially unifies the weak and electromagnetic interactions. Much more ambitious but still unestablished is grand unification, which would unifiy the strong and electroweak interactions. Even more so are superstring theories, which unify gravity as well.

Grand unification and superstring theories may involve relatively weak couplings all the way up to the Planck scale $M_P = G_N^{-1/2} \sim 10^{19}$ GeV. Possible experimental implications of such theories include supersymmetry (a relation between fermions and bosons) at the TeV $\equiv 10^3$ GeV scale; other low scale *remnants*, such as new particles or interactions; proton decay; the unification of gauge couplings when extrapolated to high energies; or possible large and/or warped extra dimenensions. Other possible extensions involve strong coupling effects at or near the TeV scale, such as compositeness or more complicated dynamic mechanisms of electroweak symmetry breaking. These may again lead to new particles and interactions at the TeV scale.

A variety of experimental and observational probes are expected to combine with theoretical advances to shed light on the physics beyond the standard model. These include high energy collider experiments at the LHC and at possible future linear e^+e^- colliders, experiments probing neutrino masses and properties, flavor physics (e.g., involving heavy quarks, rare decays, CP violation, or electric dipole moments), as well as astrophysics (e.g., type II supernova explosions) and cosmology (such as the nature of the dark matter and dark energy, and the origin of the baryon asymmetry).