The standard model (SM) of elementary particle physics

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One might think that when a term like “standard model” is used in physics, it would have a standardized, well-defined, and unambiguous meaning that has been agreed on by a majority of theoretical physicists.

However, in the case of “standard model,” this is not so. On the contrary, the actual signification of the term “standard model” depends on who is using it. In particular, the term “standard model of cosmology” is highly inappropriate because it misleadingly hints at the existence of a single cosmological model to which most physicists adhere.

THE STANDARD MODEL OF COSMOLOGY

In 1915, Albert Einstein published the general theory of relativity (GR)—a local theory for gravitation. GR is a kind of geometry that successfully describes gravitational interaction, but gives no clue to why gravity exists.

Nothing says that a working local gravity theory may be applied globally—to the entire universe. Just as nothing says that Euclidean geometry (which holds true locally on flat surfaces, where the angles of every triangle add up to 180°) may be applied globally—to a planet’s surface.

Still, in the absence of plausible alternative theories, it was natural that one should try to see if GR also might play a global role.

Therefore, after Edwin Hubble discovered that the universe is expanding, physicists tacitly postulated that: (a) gravity affects the large-scale behavior of the universe, (b) GR without modifications may be applied globally to the universe, and (c) the struggle between gravity and expansion determines the rate of expansion and thereby the fate of the universe.

These three seldom-questioned postulates led to the “Friedmann universe” (described by Alexander Friedmann’s solution to the Einstein equations with $\Lambda = 0$), which came to be regarded as the standard model of cosmology.

In this model, the universe begins as a singularity—an infinitely small, infinitely dense, and infinitely hot point.

Half a century later, the standard model’s predictions were refuted by observations. Still, its underlying postulates were not questioned. Instead, physicists tried to amend the model by artificially adding onto it new features they invented.

Today, after the introduction of an early inflationary phase and a cosmological repulsion of unknown nature and unknown time dependence (*Lambda, dark energy*, and *quintessence* are keywords), the "hot big bang" is no more a single standard model.

Thus, in his book *Faster than the Speed of Light* (2002) on the "Varying Speed of Light" (VSL) theory, João Magueijo notes on page 257 that there are "hundreds of models of inflation." Also, he mentions that inflation's competitor, VSL, has been converted "from a single theory into a large class of models" (page 223).

The main problem of the infinitely hot big bang of GR is its initial singularity. Now, the concept of "infinity" is a mathematical abstraction, and few physicists believe anymore that infinities may exist in the real world of physics. Consequently, today's cosmologists tend to believe in the idea that the universe was not born infinitely hot, but "only" immensely hot.

Still, there is no consensus on what object should replace the naked singularity of GR. Exactly how hot should that primordial object be? Exactly how dense? Exactly how many particles should it contain? How many space and time dimensions should it possess? Should all the four fundamental forces be there from the very beginning? The list of questions can be made long and the list of more or less plausible answers much longer.

In summary, talking about "a standard model of cosmology" is highly misleading because in reality there exists a myriad of competing models. Indeed, it is difficult to avoid the impression that there are as many "standard models" of cosmology as there are cosmologists.

THE STANDARD MODEL (SM) OF ELEMENTARY PARTICLE PHYSICS

Even in pure elementary particle physics, the term "standard model" is ambiguous. Thus, looking first into a dictionary of physics and then into a dictionary of science, one finds that the two dictionaries attribute different meanings to "standard model."

The entry **standard model** in *The Penguin Dictionary of Physics* (third edition, 2000) refers to *electroweak theory*, about which the dictionary writes:

"**electroweak theory** A gauge theory (also called *quantum flavourdynamics*) that provides a unified description of both the electromagnetic and weak interactions. In the Glashow–Weinberg–Salam (GWS) theory, also known as the *standard model*, electroweak interactions arise from the exchange of photons and of massive charged $W^{\pm}$ and neutral Z^0 bosons of spin 1 between quarks and leptons. The interaction strengths of the gauge bosons to quarks and leptons and the masses of the W and Z bosons themselves are predicted by the theory in terms of a single new parameter, the Weinberg angle θ_W, which must be determined by experiment. . . .

The GWS model also predicts the existence of a heavy spin 0 particle, not yet observed experimentally, known as the *Higgs boson* (see Higgs mechanism). This particle results from the so-called *spontaneous symmetry breaking* mechanism used to generate nonzero masses for the $W^{\pm}$ and Z^0 bosons and is presumably too massive to have been produced in existing particle accelerators."

Looking up **standard model** in *Oxford Dictionary of Science* (fourth edition, 1999), one is referred to *elementary particles*, about which the dictionary writes:

“**elementary particles** The fundamental constituents of all the matter in the universe. . . .
. . .

In 1978 the *standard model* was proposed as the definitive theory of the fundamental constituents of matter. In the current view, all matter consists of three kinds of particles: leptons, quarks, and mediators (see *Table of Mediators*). The mediators are the particles by which the four fundamental interactions are mediated. In the standard model, each of these interactions has a particle mediator. For the electromagnetic interaction it is the photon.

For weak interactions the force is mediated by three particles called W^+, W^-, and Z^0 bosons; for the strong force it is the gluon. Current theories of quantum gravity propose the graviton as the mediator for the gravitational interaction, but this work is highly speculative and the graviton has never been detected.”

It appears that *Oxford Dictionary of Science* best defines what ought to be included in today’s standard model (SM) of elementary particle physics. Thus, the basis of SM is formed by the experimentally confirmed quantum electrodynamics (QED), quantum chromodynamics (QCD), and electroweak (or GWS) theories.

Quantum gravity is a candidate for SM, but as long as no graviton has been observed, it cannot be generally accepted as part of SM.

The Higgs particle has not been observed, either. However, since its existence is crucial for the logical consistency of the electroweak theory, most elementary particle physicists think that the Higgs belongs to SM.

The fact that the Higgs particle is accepted in SM does not, however, mean that the so-called “Higgs mechanism” (which is out of reach of experimental physicists) should be part of SM.

THE HIGGS MECHANISM

The modern electroweak theory originates from the idea that all particles were born massless in the immense heat of the big bang, and that there was perfect symmetry between the electromagnetic and weak forces and between the particles (γ, W^+, W^-, and Z^0) that carry them. The cooling of the immensely hot universe is then thought to have triggered a “spontaneous”[!] symmetry breaking that gave particles their present masses.

The invention of this “hot Higgs mechanism” meant a breakthrough in elementary particle physics as it predicts the existence of the W and Z particles and leads to a logically consistent and highly successful model for weak interactions.

However, the Higgs mechanism does not directly predict the value of any specific physical quantity. It may be used to derive the relations

$$M_W^2 = \pi\alpha(\hbar c)^3/\sqrt{2}G_F c^4 \sin^2\theta_W \tag{1}$$

and

$$M_W/M_Z = \cos\theta_W, \tag{2}$$

but the values $M_Z = 91$ GeV/c^2 and $M_W = 80$ GeV/c^2 are only obtained after the Fermi constant G_F and the Weinberg angle θ_W have been experimentally determined.

A convincing mechanism should theoretically predict G_F and θ_W. Also, it should explain the purpose of the weak interactions—why the Z and W bosons and the three neutrinos (neutral leptons) exist in the first place.

The "cold" *Higgs–neutrino mechanism* does exactly that—and more.

THE HIGGS–NEUTRINO MECHANISM

By (1) assuming that space may be compared to a fluid for which the law of conservation of momentum holds, (2) applying the law of conservation of energy to the expanding universe, and (3) consistently adhering to the principle of maximum simplicity, one is inevitably guided by basic mathematics toward the simplest possible description of a stable material universe.

It turns out that the newborn universe is unstable. Repeatedly, it decays only to (forced by the law of conservation of energy) instantly rematerialize. This vicious circle produces increasingly complex particles and forces until, finally, the proton enters the scene.

A heavy proton cannot appear out of nothing. Its mass has to be obtained from the background photon radiation. That is, mass (or rest energy) has to be fetched from the only place where it is found—in the virtual lepton pairs appearing in the propagators of the background photons—and transferred to the quarks, which use the mass (or rest energy) they receive to build a proton-antiproton pair.

The transport of mass is handled by the Higgs–neutrino mechanism (or, more precisely, the Higgs–Z–neutrino–W mechanism). The reason for the complexity of the mechanism—and thus for the complexity of the weak interactions—is that the formation of the proton pair from quarks involves an intermediate step: formation of charged pion pairs from quarks.

In summary, the Higgs–neutrino mechanism and its role in the formation of stable matter explain why the weak interactions exist. The mechanism explains the purpose of first one and then three more Higgs bosons, the purpose of the Z particle, and the purpose of the neutrinos. The Higgs and neutrino masses are easily calculable. The Z and W masses are expected to be calculable, too. The previously so puzzling CP violation in kaon deacay finds a most simple explanation.

For details, see separate article: *Neutrino and Higgs masses.*

THE EXTENDED STANDARD MODEL (EXTENDED SM)

The standard model is a purely dynamic theory. Using Feynman diagrams it describes the interactions between elementary particles.

The extended standard model in addition assumes that a particle at the precise instant of its birth may be pictured as "static" or "stationary"—that is, may be described by a stationary equation, which is derived from a more general, time-dependent equation in which the time derivatives are set equal to zero.

Via Feynman rules, SM describes the dynamic properties of

- the massive charged spin-$\frac{1}{2}$ leptons, $\mathrm{e}^{\pm}$, $\mu^{\pm}$, and $\tau^{\pm}$,
- the massive neutrinos, or neutral spin-$\frac{1}{2}$ leptons, ν_e, ν_μ, and ν_τ,
- the massive fractionally charged spin-$\frac{1}{2}$ quarks, u and d, c and s, and t and b,
- the massive spin-1 weak gauge bosons, $\mathrm{W}^{\pm}$ and Z^0,
- the massive Higgs, or spin-0 weak gauge boson, H,
- the massless photon, or spin-1 gauge boson, γ,
- the massless gluons, or spin-1 gauge bosons, $\mathrm{g}_1, \ldots, \mathrm{g}_8$.

Further, the extended SM

- suggests that Dirac's new equation describes the newborn universe,
- explains why there exist two "heavy electrons," the tauon ($\tau^{\pm}$) and muon ($\mu^{\pm}$),
- explains the magnitudes of the particle masses,
- suggests that all particle masses are theoretically calculable (in units of m_e, say),
- predicts a precise value for the muon mass, that is, $m_\mu/m_e = 206.768\ 283\ 185(78)$,
- predicts precise values for the Higgs mass,
- predicts precise values for the neutrino masses,
- explains the purpose of the electromagnetic force,
- suggests that α (or the strength of the electromagnetic force) is calculable,
- explains the purpose of the strong force,
- explains the purpose of the weak force,
- shows that G_F (or the strength of the weak force) is theoretically predictable,
- explains the purpose of the Higgs boson,
- explains the purpose of the Z boson,
- shows that CP violation is an inevitable property of weak interaction,
- suggests that the extent of CP violation in kaon decay is predictable,
- predicts the existence of four Higgs bosons,
- explains the purpose of the neutrinos,
- explains the purpose of the W boson.

For details on the predictions, see separate article: *Predictions in cosmology.*
For details on Dirac's new equation, see separate article: *Dirac's particle.*

The extended SM implies a "predictive cosmology," which pictures how the forces and the elementary particles came to be in an initially cold and unstable universe that finally was stabilized by a "big explosion" in which antiproton decay created stable matter ($\mathrm{p\bar{p}} \rightarrow \mathrm{pe}^-$ plus radiation) at the same time as it heated matter to about a billion Kelvin.