Strange terms used in used in theoretical physics (experimenters' view)

Naturalness - An aesthetic criterion (not a physical one) leading to expectation that all free parameters of physical constants appearing in a physical theory should have relative values "of order 1".
This is not a property of the Standard Model where unexplained parameters e.g., masses of fundamental particles vary from each other by many orders of magnitude
m(electron) = 0.51 MeV vs m(top quark) = 173.2 GeV
translated to the size of the corresponding couplings to Higgs boson

In the basic formulation we have two basic constants of nature
for weak interactions
Fermi constant $G_F/(hc)^3 = 1.166\ 10^{-5}$ Gev-2
for gravitation
gravitational constant $G_N = 6.67\text{x}10^{-11}\ m^3kg^{-1}s^{-2} = 6.7\text{x}10^{-39}\ hc\ (GeV/c^2)^{-2}$

Strange terms used in used in theoretical physics

Fine-tuning – occurs when the parameters of a model must be adjusted precisely in order to agree with observations. Models/theories that require fine-tuning adjustments may indicate that there are missing pieces in the theory. This is particularly important for cosmological models that have no explanation for the size of various constants (e.g. cosmological constant, inflation, etc.)

Hierarchy problem – large discrepancy between e.g., weak force and gravity.
Weak force is 10^{32} times stronger than gravity.
In general, this problem occurs when fundamental value of a parameter used in Lagrangian is different from its effective value measured in experiment. The measured, fundamental value is changed by renormalization that includes quantum corrections.

In theoretical approach – the quantum corrections are usually power-law divergent indicating that the effect is dominated by very small distances that we have not probed with present experiments. Theorists “solve” the problem by inventing theories that provide cancellations between large terms. An example of such theory is Supersymmetry.

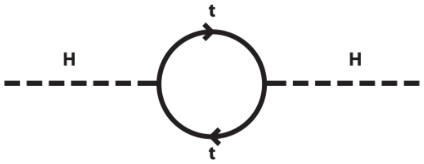
Current theoretical prejudice included in the cosmological models is based on unification of forces at very high energy. This poses a number of problems e.g., why Higgs mass is so much smaller than the Planck mass (m(Higgs) = 125 GeV vs $m_P = 1.22 \times 10^{19}$ GeV)

In cosmology and particle physics reduced Planck mass is the maximum mass of a point object that can hold a single elementary charge

$$m_P = \sqrt{\frac{\hbar c}{8\pi G}} \approx 2.435\times 10^{18}\, GeV / c^2$$

where G is the gravitational constant. It has a mass approximately of a mass of a flea. Larger masses would create black holes.

An example of theory that provides cancellations of higher order quantum corrections terms is Supersymmetry where the supersymmetric particles have spins shifted by ½
i.e., fermionic quarks and leptons become bosons and gauge particles become fermions.
Since the signs of terms calculated using Feynman rules change going from fermions to bosons the loop corrections would cancel out (exactly if supersymmetric partners would have the same masses as the known particles).



Particle content in Supersymmetry

Each left(right)-handed quark (spin = ½) has a scalar (spin 0) partner quark called squark.
sup, sdown, sstrange, scharm, sbotton, stop $q_L(q_R)$
The subscripts L and R do not refer here to spin but the the corresponding partner quark.
Similarly leptons have corresponding spin 0 partners called sleptons.
None has been seen so far so if they exist they must have large masses.

The gauge boson have corresponding spin ½ partners:

gluinos (spin ½ supersymmetric gluons)
winos (spin ½ supersymmetric partners of W bosons)
binos (spin ½ supersymmetric partners of Z boson)
gravitino (spin 3/2 supersymmetric partner of graviton)

The model requires an extension of the Higgs sector. There would be two separate scalar Higgs doublets leading to 3 neutral and a pair of charged Higgses with their supersymmetric partners spin ½ Higgsinos.

The sparticles would have their own decay chains and interactions analogous to those in the Standard Model. The lowest mass sparticle cannot decay and is stable. If charged it should likely have been seen already so the expectation is that it is neutral and does not decay to usual pions, kaons etc, but instead generate Missing Energy signature (E_T^{miss} in the LHC nomenclature)

Strong CP problem

CP symmetry states that the laws of physics should be the same if a particle were interchanged with its antiparticle (C symmetry) and then left and right were swapped (P symmetry).

Parity (P) – space reflection

Classical vector changes sign $\vec{x} \xrightarrow[P]{} -\vec{x}$

Axial vector e.g., orbital angular momentum L = x × p is left invariant.

Spin and total angular momentum do not change sign.

Charge conjugation (C)

Charge conjugation changes particles into antiparticles without affecting their momenta or spin.

In quantum mechanics the wave function of a particle has an arbitrary phase that is not observable. One can choose the phase so that it becomes 0 for a physical state.

Any particular term in the Lagrangian can be therefore conserving CP.

CP violation occurs when the two or more terms on the Lagrangian cannot be made invariant simultaneously resulting in an explicit phase.

In weak interactions P symmetry is violated maximally.

In electroweak theory CP is violated via phase in the CKM matrix as gauge bosons couple to chiral currents.

From T. Mannel, Theory and phenomenology of CP violation. Nucl. Phys. B167(2007)170.

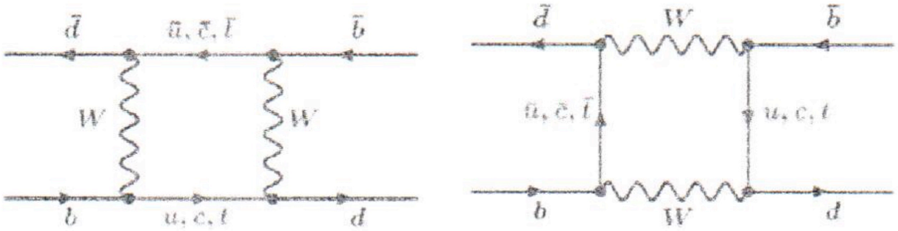


Figure 2. The box diagramms mediating $\Delta F = 2$ transitions in the standard model.

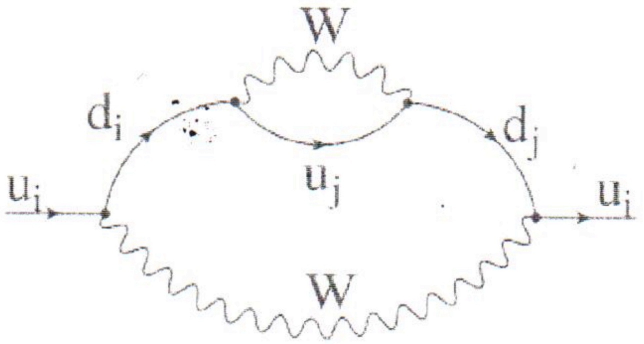


Figure 3. Feynman Diagram leading to an electric dipole moment for the up quark.

Strong CP problem

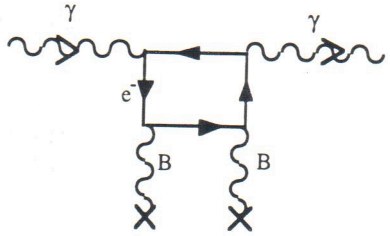
One of the underlying assumptions in the particle physics theory is that any process that is not explicitly forbidden by some principle or conservation law is mandatory i.e., must happen with some probability.
The QCD Lagrangian can have a term that is not excluded by any known law that can include an arbitrary phase

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{n_f g^2 \theta}{32\pi^2}F_{\mu\nu}\tilde{F}^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m e^{i\theta'\gamma_5})\psi$$

In contrast the electroweak interactions QCD gluons couple to (non-chiral) vector currents.
For non-zero value of the angle θ in the chiral quark mass term one expects CP symmetry to be violated. Experimental data do not indicate any CP violation in strong interactions.
For example the electric dipole moment of the neutron is estimated in QCD to be ~ $10^{-16} \times \theta$ e-cm while the experimental upper limit is $|\theta| < 10^{-26}$ e-cm.

A priori θ can have any valueo between 0 and 2π. So one has to explain why the angle θ is either zero or very, very small.
Early attempt was to assume that one of the quarks masses is equal to zero. That would allow to eliminate phase term from the calculations. However, there is substantial evidence that all quarks have non-zero masses,

There have been several proposals how to deal with the strong CP problem.
All of them invoke new physics.
The most popular is **Peccei-Quinn** theory which proposes new global U(1) symmetry which includes complex, scalar field that is charged. The new effect dynamically cancels the term in the Lagrangian which carries the parameter θ eliminating CP violation in strong interactions. It also predicts existence of new particles called **axions.**
Axion mass is not defined by theory but should be small and greater than 10^{-11} x m(electron).
Low mass axion is a candidate for dark matter. It ban be detected by conversion to phootons in a strong magnetic field.
Searches include photon conversion experiments based on rotation of plarisationof light in a magnetic field, axions streaming from the Sun, resonances formed in RF cavities, etc.
In supersymmetry there would be both scalar and femionic superpartner with the fermionic called axino and scalar one called either saxion or dilaton.
No positive results have been observed to date.



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