

Alternative Solution of Strong CP

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In this talk I begin with some general discussion of the history of CP violation, then move on to aspects of a spontaneous CP violation model including the production of new particles at LHC, implications for B decay, generalized Cabibbo mixing and a reevaluation of kaon CP violation. Finally there is a summary.

Introduction

My talk is the only non-axion talk at this Workshop but its inclusion shows the broadmindedness of Pierre Sikivie. The only objection I have to the axion work of Peccei and Quinn is its non-uniqueness. I'll describe extensions of the Standard Model which solve the strong CP problem without an axion, and have the advantage of addressing CP violation. Due to the time available, I will be able to give just an impressionistic view.

1. History

The parity operation is a symmetry of Newton's Laws provided we assume a strong form of the Third Law: Action and Reaction are equal and opposite and directed along the line of centers. For quantum mechanics, Parity was introduced by Wigner in 1927[1]. The violation of P was first entertained by Lee and Yang in 1956[2]; it was quickly verified by Madame Wu[3] and others [4].

Time reversal T is an invariance of Newton's Laws. In quantum mechanics T was introduced as the now-familiar anti-unitary operator by Wigner[5]. [T violation was studied in classical statistical mechanics earlier by Boltzmann and Panlevé, but T violation in microscopic laws was not seriously questioned until 1964.]

The operation of charge conjugation (C) could hardly be conceived of before the Dirac equation[6] in 1928 predicted the e^+ , discovered in 1932. The C invariance of quantum electrodynamics was first discussed by Kramers[7] in 1937.

The invariance under CPT was proven for

quantum field theory in 1954 by Luders[8] under the weak assumptions of Lorentz invariance and the spin-statistics connection.

After Lee and Yang, but before P violation was discovered, Landau[9] suggested that CP is an exact symmetry.

In [10] CP violation was discovered in the decay of neutral kaons. The longer-lived CP eigenstate K_L was observed to decay 0.2% of the time into $\pi\pi$, disallowed if CP is exact. The CP violation is characterized by the parameter ϵ . Since CP violation has never been seen outside of the kaon system, ϵ is the only accurately measured (to within 1%) CP violation parameter.

In a remarkable paper containing an all-time favorite idea in particle theory, in 1966 Sakharov[11] proposed that the baryon number of the universe arose due to a combination of three ingredients: (1) B violating interactions. (2) Thermodynamic disequilibrium. (3) CP Violation.

When GUTs became popular, Yoshimura[12] and others illustrated this idea. More recently baryogenesis at the electroweak phase transition is discussed based on the same three ingredients.

In 1973, Kobayashi and Maskawa(KM)[13] proposed their mechanism for CP violation assuming, with great foresight, three fermion generations. The issue now is whether KM is the full explanation of the observed CP violation.

In 1976 't Hooft[14] emphasized the strong CP problem that a parameter $\bar{\theta}$ in QCD must be fine-tuned to $\bar{\theta} < 10^{-9}$ to avoid conflicting with the upper limit on the neutron electric dipole moment.

In the decade of the 1980s, the areas of weak

CP violation and strong CP proceeded along largely separate tracks.

Having mentioned time-honored classics of the subject of CP, in the rest of the talk I shall specialize to six recent papers on a specific CP model - the aspon model - published: two[15,16] in 1991, one[17] in 1992, one[18] in 1994, one[19] in 1997, and finally one in 1998[20].

2. Aspon Model

Because QCD has a possible term involving $\bar{\theta}$ in its lagrangian, there is the potential for unacceptably large CP violation. One approach which is much less motivated now than twenty years ago is to introduce a color-anomalous $U(1)$; a second is to assume the up quark is massless, although this clashes with successes of chiral perturbation theory. The third direction, exemplified by the aspon model is to assume CP is a symmetry of the fundamental theory and to arrange that $\bar{\theta}$ is zero at tree level, remaining sufficiently small from radiative corrections.

In the aspon model the gauge group of the standard model is extended to $SU(3) \times SU(2) \times U(1) \times U(1)_{new}$. The new charge Q_{new} is not carried by any of the fields of the SM. One additional doublet of Dirac quarks (U, D) with charge $Q_{new} = 1$ is introduced, together with two complex singlet scalars χ^α , $\alpha = 1, 2$.

The χ^α acquire VEVs with a non-zero relative phase, spontaneously breaking both the gauged $U(1)_{new}$ and CP. The gauge boson of $U(1)_{new}$ becomes massive by the Higgs mechanism and is called the "aspon".

The Yukawa couplings with χ involve the right-handed U and D but not the left-handed counterparts. As a result there are zeros[21] in the 4×4 quark mass matrices such that although there are complex entries the determinant is real. Hence $\bar{\theta} = 0$ at tree level.

Such a mass matrix is diagonalized by a bi-unitary transformation which is conveniently expanded in the small parameters $x_i = F_i/M$ where F_i are the off-diagonal elements and M is the Dirac mass. We may regard the x_i as independent of the family number i and simply write $|x_i| = x$. It turns out that x is constrained to lie in the

window $3 \times 10^{-5} < x^2 < 10^{-3}$ by the constraints of $\bar{\theta}$ and of CP violation.

2.1. FCNC

Since we have introduced right-handed doublets, a first concern is with the size of the induced Flavor-Changing Neutral Currents (FCNC). It turns out that these are more than adequately suppressed.

2.2. $\bar{\theta}$

At one loop level $\bar{\theta}$ acquires a non-zero value and this leads to an upper limit on the product (λx^2) where λ is the coefficient of the quartic coupling $|\phi|^2|\chi|^2$ between the standard Higgs ϕ and the χ fields.

2.3. Weak CP Violation

Fitting to the CP violation parameter ϵ and to the allowed range for $Re(\epsilon'/\epsilon)$ gives an upper limit on the symmetry breaking scale for $U(1)_{new}$ of about 2TeV. One thus predicts that, assuming the gauge coupling is not much larger than the others of the standard model, the new particles Q and A lie well below 1TeV. This fits ones intuition that if the new states are too heavy the diagrams contributing to CP violation in the kaon system will be too small.

3. Production of A and Q at LHC

Production of $\bar{Q}Q$ is dominated by gluon fusion diagrams just like $\bar{t}t$ production. The aspon A can be bremsstrahlunged from a heavy quark. Detailed calculations show that the cross-section for aspon production is a few picobarns corresponding to a few tens of thousands of events per year at LHC.

Of special interest is the decay width of A which depends sensitively on the A mass relative to the Q mass M. For the most suppressed decay, when $M(A) < M(Q)$, the decay width can be as small as 1KeV which is striking for a particle weighing several hundred GeV!

4. B Decay

The KM mechanism can be nicely checked from the unitarity triangle formed by the com-

plex numbers in the equation:

$$V_{ub}^*V_{ud} + V_{tb}^*V_{td} + V_{cb}^*V_{cd} = 0 \quad (1)$$

with corresponding angles α , β , and γ . Using the expansion of the CKM matrix as a power series in the Cabibbo angle[22], it is profitable to define the ratios:

$$R_b = \left| \frac{V_{ud}^*V_{ub}}{V_{cd}^*V_{cb}} \right| \quad (2)$$

and

$$R_t = \left| \frac{V_{cd}^*V_{tb}}{V_{cb}^*V_{cb}} \right| \quad (3)$$

Clearly if the angle β , for example, is a significant value, well away from zero or π (as would follow if the KM mechanism is the full explanation of the CP violation in kaon decay), the $R_b + R_t > 1$.

It is well-known[23] how to establish the angle β from the expected data on B decay coming from the B Factories under construction at SLAC and KEL Laboratories.

4.1. CP Asymmetries in B Decay

In the aspon model the 3×3 mixing matrix for the light quarks is a real orthogonal one up to corrections of order x^2 . This means that the CP asymmetries of B decay are predicted to be at least three orders of magnitude smaller than predicted by the KM mechanism.

In a general way, we may say that the KM mechanism is special in that the CP violation in B decay is enhanced by a factor $(m_t/m_c)^2 \sim 10^4$ relative to that in K decay. In most alternative models of CP violation such as the aspon model, there is no reason to expect this enhancement.

A clear prediction of the aspon model is that, to within less than 0.1%, $R_b + R_t = 1$. An unbiased study of the present data shows that this is well within the present range.

5. Kaon system reevaluated

The value of $|\epsilon_K| = 2.26 \times 10^{-3}$ implies (from aspon exchange) that

$$\kappa/x^2 = 2.8 \times 10^3 GeV \quad (4)$$

which, given the range for x^2 , implies that $29TeV > \kappa > 870GeV$ from which the aspon mass is expected in the range 260GeV to 8.7TeV.

Contributions to $Re(\epsilon'/\epsilon)$ come from tree diagrams and penguin diagrams. A careful comparison to the standard model gives a suppression of at least two orders of magnitude. Consequently, observation of a value above 10^{-4} would exclude this model.

6. Summary

The main attractions of the aspon model are that it solves the strong CP problem, accommodates weak CP violation, and makes testable predictions. A reader who wishes to know more may consult the References listed.

Acknowledgments

This work was supported in part by the US Department of Energy under Grant No. DE-FG05-85ER-40219.

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