CPV phenomenology of two Higgs doublet models

Satoru Inoue1, Michael J. Ramsey-Musolf1,2, Yue Zhang2
1Amherst Center for Fundamental Interactions, University of Massachusetts Amherst, 2California Institute of Technology

Motivation

Now that the Higgs boson is discovered, it is natural to ask if there could be other scalars. New scalars are especially interesting in the context of baryogenesis. Not only can they introduce new sources of CP violation, they can also strengthen the electroweak phase transition, which could allow baryogenesis at that time.

Two Higgs doublet models (2HDM) are some of the simplest scalar extensions, and they can act as an effective theory for supersymmetric (SUSY) models whose scalars are lighter than other non-Standard Model (SM) particles. In an effort to explore the viability of baryogenesis in 2HDMs, we investigate the current and future bounds on CP violation in 2HDMs, coming from electric dipole moment (EDM) experiments.

CP-violating two Higgs doublet model

2HDM is the SM plus another copy of the Higgs doublet. Both doublets acquire nonzero vacuum expectation values after symmetry breaking, and the ratio between them define the β angle.

\[ \phi_i \rightarrow \left( \frac{H_i^+}{\sqrt{2}} (v_1 H_i^0 + i A_i^0) \right), \quad i = 1, 2, \quad \tan \beta = \frac{v_2}{v_1} \]

We will focus on the so-called type-II 2HDM, which has the following Yukawa structure, identical to SUSY extensions of SM (see paper for analysis of type-I 2HDM):

\[ \mathcal{L}_Y = -Y_\ell \bar{\ell} (i \gamma_5 \tau_2) \phi_i \ell R - Y_d (i \tau_2) \phi_i d R - Y_L \phi_i \ell L + h.c. \]

CP violation in the model comes from the Higgs potential:

\[ V = \frac{\lambda_1}{2} |\phi_1|^4 + \frac{\lambda_2}{2} |\phi_2|^4 + \lambda_3 |\phi_1|^2 |\phi_2|^2 + \lambda_4 |\phi_1|^2 |\phi_2|^2 + \frac{\lambda_5}{2} \left[ |\phi_1|^4 + |\phi_2|^4 \right] + h.c. \]

where \( \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5 \) are CP-violating parameters.

In the absence of CP violating terms, 2HDM has 5 scalars: 2 charged Higgs (H±), 2 CP-even neutral Higgs (H0), and 1 CP-odd scalar (A). The effect of CP violating terms is to mix the CP-even and the CP-odd states. We parameterize the rotation matrix to diagonalize the neutral Higgs masses using 3 angles, \( \alpha_1, \alpha_2, \alpha_3 \):

\[ (H_1^0, H_2^0, A^0) = (h_1, h_2, h_3) \times (R_{21}(\alpha_2) R_{12}(\alpha_3) R_{12}(\alpha_1 + \pi/2)) \]

Roughly, \( \alpha \) shows how much of \( H_1 \) and \( H_2 \) contribute to the lightest Higgs, \( h_1 \), \( h_2, h_3 \) describes the mixing of the CP-odd scalar into \( h_1 \), and \( \alpha_3 \) is associated with the heavy Higgs. We assume that \( h_1 \) is the 125GeV scalar that has been discovered at the LHC.

Crucially, CP-violating mixing results in each of the neutral Higgs having both scalar and pseudoscalar couplings to fermions. \( ^1 \)

Results

From LHC data, we find that the α angle needs to be around \((\beta - \pi/2)\), in order to reproduce the SM-like production rate and branching fractions for the Higgs. We fix the masses of the heavy neutral Higgs at 400 and 450GeV, and charged Higgs at 420GeV, and place limits on \( \alpha_1 \) using EDMs.

There are 3 kinds of CP-violating dimension-6 operators that need to be considered: fermion EDMs, quark chromo-EDMs, and Weinberg 3-gluon operator.

Sample Feynman diagrams for Weinberg operator, chromo-EDM, and EDM

\[ \text{Sample Feynman diagrams for Weinberg operator, chromo-EDM, and EDM} \]

2-loop diagrams are important for EDM and chromo-EDM of light fermions, because 1-loop diagrams are suppressed by 2 small Yukawa couplings.

ACME experiment on TlO molecules is the easiest to interpret. The dominant effect is the electron EDM.

\[ \text{ACME excludes the blue regions} \]

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\[ \text{Chosen to meet flavor and precision electroweak constraints.} \]

Conclusions

ACME experiment, through electron EDM, places the strongest constraints on CP-violating mixing angle \( \alpha_1 \), which is of order 0.01 or smaller for most values of \( \tan \beta \).

Neutron and atomic experiments can become competitive to current ACME limits with future improvements, but theoretical uncertainties need to be reduced.

A study of baryogenesis scenarios would bound CP violation from below, giving experimentalists a target to shoot for (or shoot at).

Contact

Satoru Inoue
sinoue@umass.edu

Footnotes:

1 In the SM, there are also 2 Goldstone modes that give mass to the weak gauge bosons and are not propagating degrees of freedom.