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Signals of New Physics in $B_q^0 - \overline{B_q^0}$ Mixing

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Abstract : Discrepancy between the experimental results for the same-sign dimuon charge asymmetry measured by the D0 Collaboration and the corresponding standard model (SM) predictions gives the possibility of having new physics (NP) effects in neutral B-meson mixing. In this review article, we discuss the current status of $B_q^0 - \overline{B_q^0}$ (q = d, s) mixing within the SM as well as the signals of NP beyond the SM.

Keywords: $B_q^0 - \overline{B_q^0}$ mixing, Neutral currents, Models beyond the standard model, Z' boson

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1. Introduction

The standard model (SM)[1–4]of particle physics is now known to be the most successful theory in describing the contemporary understanding of the fundamental fermions and their basic interactions except gravitation. Six quarks, six leptons (with their antiparticles), force carrying bosonsand Higgs boson are the building blocks of the SM.But, yet we have so many unanswered basic questions in this wellestablished theory: CP violation, neutrino oscillation, dark matter & dark energy, matter-antimatter asymmetry etc. These questions provoked the physicists to search for theories which can answer those hierarchy puzzles by going beyond the limits of the SM. Hence the theories which are the extensions of the SM or goes beyond the SM are the source of many unknown theories, termed as new physics (NP). There are two methods to investigate the physics beyond the SM: (i) Direct search for new particles where the energy of the colliders raised hugely, (ii) Indirect search by increasing the experimental precision on the data of different SM processes where NP effects can manifest themselves.Among different sectors of particle physics flavoroscillation or particle –antiparticle mixing is one of the most efficient paths which can be followed to predict NP effects.

Neutral B-mesons(B_d^0,B_s^0) mixing [5-9]is predicted with in the SM under strict guidelines.This phenomenon is called flavor oscillation. Two parameters describing the time evolution of the $B^0$are its lifetime τ(how long it lives) and its mixing frequency Δm(the average rate at which B^0transforms in to $\overline{B^0}$and vice versa). The key idea of mixing is that, mixing occurs because the flavoreigenstates are not equivalent to the masseigenstates; *i.e.,* one cannot measure both the mass and the flavor of the particlesimultaneously. As such, time evolution (according to the Hamiltonian governing thesystem) will rotate the flavoreigenstates as a function of time while it preserves themass eigenstates.

$B_q^0 - \overline{B_q^0}$ mixing (q = d, s) plays an outstanding role in searching new physics (NP) beyond SM as, (i) meson-antimeson oscillations occur at time scales which are sufficiently close to the meson lifetimes to permit their experimental investigation, (ii) the SM contribution to meson-antimeson mixing is loop-suppressed and comes with two or more small elements of the CKM matrix, (iii) the decays of oscillating mesons give access to many mixing-induced CP asymmetries through the time-dependent study of decays into CP-eigenstates, which in some cases one can relate to the parameters of the underlying theory with negligible hadronic uncertainties.

The phenomenon of CP violation is an essential ingredient to explain the asymmetry between the matter and antimatter in the universe. CP violation arises in the Yukawa-sector via quark mixing and it is described by a complex parameter in the Cabbibo-Kabayashi-Maskawa (CKM) matrix.It is observed that CP violation provided by the CKM mechanism is not sufficient to explain the observed abundance of matter in the universe. Therefore, the study of CP violation in different phenomenon is an active area of research in the present scenario. The study of CP violation in the B_q^0system offers an excellent opportunity to detect possible deviations from SM predictions. Moreover, it is expected that the SM CP violating effects are suppressed in comparison to CP violation B_q^0meson decays. CP violation in the B-meson system was first discovered via indirect CP violation in 2002 [10-11]. The direct CP- violation in B-meson system was discovered later in 2004 [12].

2. Signals of new physics in $B_q^0 - \overline{B_q^0}$ mixing

The time evolution of the $B_q - \overline{B}_q$ system can be expressed by the time-dependent
Schrodinger equation:

$$i\,\frac{d}{dt}\begin{pmatrix} |Bq(t)\rangle \\ |\overline{B}q(t)\rangle \end{pmatrix} = \left(M - i\,\frac{\Gamma}{2}\right)\begin{pmatrix} |Bq(t)\rangle \\ |\overline{B}q(t)\rangle \end{pmatrix} \quad . \tag{1}$$

Here, M and Γ are 2×2 Hermitian matrices. M is the mass matrix and Γ is the decay matrix. Here $|Bq(t)\rangle$ denotes the state of a meson produced as a Bq, similarly the definition for $|\overline{B}q(t)\rangle$. The off-diagonal elements are $M_{12} = M_{21}^*$ and $\Gamma_{12} = \Gamma_{21}^*$. In the SM, contributions to M_{12} and Γ_{12} come from the box diagram (Fig.1) [13]. Γ_{12} is not significantly modified by new physics because Γ_{12} receives major contributions from CKM favoured $b \to c\bar{c}s$ decays in the SM, and the SM result $\Gamma_{12} << M_{12}$ is unlikely to change [14, 15]. But, M_{12} is almost induced by short-distance physics. Within the SM the top quarks give the dominant contribution to $B_q - \overline{B}_q$ mixing [16, 17]. This contribution is suppressed by four powers of the weak coupling constant and two powers of CKM matrix element $|V_{ts}| \cong 0.041$. Hence new physics can compete with the SM.The mass eigenstates at time t = 0, $|B_q\rangle_L$ and $|B_q\rangle_H$ are linear combinations of $|B_q\rangle$ & $|\overline{B}_q\rangle$:

Lighter eigenstate: $|B_q\rangle_L = p_L\,|B_q\rangle + q_L\,|\overline{B}_q\rangle$

Heavier eigenstate: $|B_q\rangle_H = p_H\,|B_q\rangle - q_H\,|\overline{B}_q\rangle$, (2)

with the normalization $|p_{L,H}|^2 + |q_{L,H}|^2 = 1$ and the CP- invariance (in mixing) would require that $p_H = p_L = p$ and $q_H = q_L = q$ and that $(p/q) = 1$.

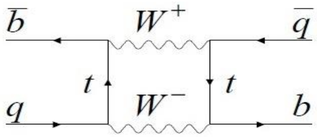

Fig. 1: Box diagram for $B_q^0 - \overline{B_q^0}$ mixing (*q* = *d*, *s*).

The mass difference and decay width difference of the physical 'heavy' and 'light' mass eigenstates are given by the off-diagonal elements by [18]

$$\Delta M_q \equiv M_H^q - M_L^q = 2\left|M_{12}^q\right|, \quad (3)$$

$$\Delta \Gamma_q \equiv \Gamma_L^q - \Gamma_H^q = 2\left|\Gamma_{12}^q\right| \cos\phi_q . \qquad (4)$$

The CP violation inmixing is described by the weak mixing phase ϕ_q (i.e. The CP phase difference between M_{12}^q and Γ_{12}^q), defined as:

$$\phi_q = \phi_M - \phi_\Gamma = \arg\left(- \frac{M_{12}^q}{\Gamma_{12}^q} \right). \qquad (5)$$

Thus a measurement of the mixing phase gives us direct information about the phases i.e. the amount of CP violation, of the CKM elements.

In the SM, the $B_q^0 - \overline{B_q^0}$ mixing is due to the weak interaction. At the lowest order, this mixing is described by box diagrams involving two W bosons and two up-type quarks [7, 19]. In this case, the long range interactions arising from intermediate virtual states are negligible because the large B mass is off the region of hadronic resonances. In the SM, M_{12} and Γ_{12}^q are computed from the box diagram and read as [7, 20]:

$$M_{12}^q = \frac{G_F^2 M_W^2 M_{B_q} \eta_{B_q}}{12\pi^2} f_{B_q}^2 B_{B_q} S_0(x_t)\left(V_{tq}^* V_{tb}\right)^2 \qquad (6)$$

$$\Gamma_{12}^q = \frac{G_F^2 m_b^2 \eta_B^{/} M_{B_q} f_{B_q}^2 B_{B_q}}{8\pi} \times \left[\left(V_{tq}^* V_{tb}\right)^2 + V_{tq}^* V_{tb} V_{cq}^* V_{cb}\, O\left(\frac{m_c^2}{m_b^2}\right) + \left(V_{cq}^* V_{cb}\right)^2 O\left(\frac{m_c^4}{m_b^4}\right) \right], \qquad (7)$$

where G_F is the Fermi constant, M_W is the W boson mass, m_i is the mass of quark *i*, $x_t = m_t^2 / M_W^2$; M_{B_q}, f_{B_q} and B_{B_q} are the B_q^0 mass, weak decay constant and bag parameter respectively. The Inami–Lim function $S_0(x_t)$ [21] is approximated as $0.784\, x_t^{0.76}$, V_{ij} are the elements of the CKM matrix [22]; η_B are

QCD corrections. Both M_{12} and Γ_{12}^{q} can be complex because they depend on CKM matrix elements.

The determination of $B_q^0 - \overline{B_q^0}$ mass difference has been a major objective of particle physics. In the SM, the mass difference ΔM_{B_d} is proportional to the combination $\left(V_{td}^{*}V_{tb}\right)^2$ of CKM matrix elements. Since the matrix element V_{ts} is larger than V_{td}, the expected mass difference ΔM_{B_s} is higher. The mass differences ΔM_{B_d} and ΔM_{B_s} can be used to determine CKM matrix elements V_{td} and V_{ts} respectively [18, 23]. In the SM, $B_s^0 - \overline{B_s^0}$ and $\mathrm{B_d^0} - \overline{\mathrm{B_d^0}}$ mass differences are found to be [24]:

$$(\Delta M_{B_d})_{SM} = (0.528 \pm 0.078) ps^{-1}, (\Delta M_{B_s})_{SM} = (18.3 \pm 2.7) ps^{-1} \quad (8)$$

The experimental averages for $B_d^0 - \overline{B_d^0}$ and $B_s^0 - \overline{B_s^0}$ mass differences are given by HFAG [24, 25]:

$$\Delta M_{B_d} = 0.510 \pm 0.003\,\mathrm{ps}^{-1}, \Delta M_{B_s} = 17.757 \pm 0.021\,\mathrm{ps}^{-1}. \quad (9)$$

The LHCb collaboration [24, 26] has measured

$$\Delta \mathrm{M}_{\mathrm{B_d}} = (0.503 \pm 0.011\,(\mathrm{stat.}) \pm 0.013\,(\mathrm{syst.}))\,\mathrm{ps}^{-1},$$

$$\Delta \mathrm{M}_{\mathrm{Bs}} = (17.768 \pm 0.023\,(\mathrm{stat.}) \pm 0.006\,(\mathrm{syst.}))\,\mathrm{ps}^{-1}. \quad (10)$$

The measurements agree with the SM predictions, but the theoretical uncertainties are considerably larger than the experimental ones. Hence, there is still plenty of room for sizable new physics effects [27].

In the SM the decay width difference for $B_d^0 - \overline{B_d^0}$ and $B_s^0 - \overline{B_s^0}$ oscillation are obtained as [24, 28]:

$$\Delta\Gamma_d^{\mathrm{SM}} = (2.61 \pm 0.59) \times 10^{-3}\ \mathrm{ps}^{-1} \text{ and } \Delta\Gamma_s^{\mathrm{SM}} = (0.088 \pm 0.020)\ \mathrm{ps}^{-1} \quad (11)$$

The decay rate difference $\Delta\Gamma_{\mathrm{d}}$ measured by the D0 collaboration [29] is

$$\Delta\Gamma_d / \Gamma_d = (2.63 \pm 0.66) \times 10^{-2} \quad (12)$$

which differs from the SM prediction [24]

$$\left(\frac{\Delta\Gamma_d}{\Gamma_d}\right)^{\text{SM}} = (3.97 \pm 0.90)\times 10^{-3} \tag{13}$$

Above value provides an experimental bound which is an order of magnitude larger than the SM prediction. Recently [30, 31], three different sources (CKM unitarity violations, current-current standard model operators and operators $(\bar{d}b)(\bar{\tau}\tau)$) for the enhancement of $\Delta\Gamma_{\text{d}}$ have been considered and have found sizable deviations from its standard model value. It may be suggested that the discrepancy between theory and experiment for same-sign dimuon charge asymmetry could be eliminated if $\Delta\Gamma_{\text{d}}$ gets enhancement through non-standard model physics.

The same-sign dimuon charge asymmetry from the semi-leptonic $(s\ell)$ decay of $B_{s,d}$ meson is given by [32, 33]:

$$A_{s\ell}^{b} = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}, \tag{14}$$

where N^{++} corresponds to each B hadron decaying semi-leptonically to $\mu^{+}X$ and similarly N^{--} to $\mu^{-}X$. The individual flavor-specific CP asymmetries contribute to the total asymmetry $A_{s\ell}^{b}$ as [34, 35]:

$$A_{s\ell}^{b} = (0.594 \pm 0.022)\, a_{s\ell}^{d} + (0.406 \pm 0.022)\, a_{s\ell}^{s}. \tag{15}$$

where, the individual flavor-specific charge asymmetry $a_{s\ell}^{q}$ is related to the mass and width differences in the $B_q^0 - \overline{B_q^0}$ system as [32, 33],

$$a_{s\ell}^{q} = \text{Im}\frac{\Gamma_{12}^{q}}{M_{12}^{q}} = \frac{|\Gamma_{12}^{q}|}{|M_{12}^{q}|}\sin\phi_q = \frac{\Delta\Gamma_q}{\Delta M_q}\tan\phi_q \tag{16}$$

The SM expectations for the observables $a_{s\ell}^{d}$ and $a_{s\ell}^{s}$ is given as[24]

$$a_{s\ell}^{d} = (-4.7 \pm 0.6)\times 10^{-4} \text{ and } a_{s\ell}^{s} = (2.22 \pm 0.27)\times 10^{-5} \tag{17}$$

As per the D0 result [37], the values of these asymmetries are given as

$$a_{s\ell}^{d} = (-0.62 \pm 0.43)\times 10^{-2} \text{ and } a_{s\ell}^{s} = (-0.82 \pm 0.99)\times 10^{-2} \tag{18}$$

The departure of theses CP asymmetries from the SM value is quite significant.The measurement of a large same-sign charge asymmetry $A_{s\ell}^{b}$ by the D0 experiment at the Tevatron gives:

$$A_{s\ell}^{b} = \left(-7.87 \pm 1.72 \pm 0.93\right) \times 10^{-3} \text{ [34] and}$$

$$A_{s\ell}^{b} = \left(-4.96 \pm 1.53 \pm 0.72\right) \times 10^{-3} \text{ [29]} \tag{19}$$

These numbers depart noticeably from SM expectations [8, 36]:

$$\left(A_{s\ell}^{b}\right)_{SM} = \left(-2.44 \pm 0.42\right) \times 10^{-4} . \tag{20}$$

This discrepancy may be interpreted as a hint of physics beyond the SM. In order to explain this observed asymmetry, additional CP violation source is strongly required in $B_{s,d}$ mixing.Considering NP contribution in the Wilson coefficients Botella*et al.*[36] have calculated

$$\Delta\Gamma_{d} = 3.25 \times 10^{-3} \text{ ps}^{-1} \text{and } a_{s\ell}^{d} = -1.92 \times 10^{-3} , \tag{21}$$

$$\Delta\Gamma_{s} = 0.11 \text{ ps}^{-1} \text{and } a_{s\ell}^{s} = 7.1 \times 10^{-5} . \tag{22}$$

Several researchers have also tried to obtain a sizable NP contribution in different models such as the lepto-quark models [37] , the MSSM with non-minimal flavor violation [38], R-parity violating supersymmetric model [39], split SUSY model [21], Z' model [39, 40] and a fourth generation model [41]. In [42], Sahoo *et al.* have calculated same-sign dimuon charge asymmetry for $B_q^0 - \overline{B_q^0}$ system by considering the effect of Z'-mediated flavour-changing neutral currents (FCNCs)which give sizable contributions to the $B_q^0 - \overline{B_q^0}$ mixing and the value is enhanced from its SM prediction.

3. Conclusion

The low energy observables in $B_q^0 - \overline{B_q^0}$ oscillation play an important role for an indirect search of NP. The theoretical description of B-meson oscillation involves the elements M_{12}^{q} and Γ_{12}^{q} of the mass and decay matrices, which are determined by precise measurement of ΔM_q and $\Delta\Gamma_q$. Theoretical uncertainties still permit new-physics contributions to M_{12}^{q} and Γ_{12}^{q}. The study of CP violation phenomena in the neutral B meson system is a very active area of research because the experimental result from D0 collaboration for the same-sign dimuon charge asymmetry differs from the SM expectation distinctly. CP violation is an essential ingredient to explain the asymmetry between the matter and antimatter in the universe. Till date several theoretical NP models have achieved the enhanced values of the observables by considering NP contribution compared to SM values, yet those are not enough to reproduce the D0 measurement of $A_{s\ell}^{b}$. The existence of NP would be drawn by the investigation of CP violation in mixing extracted from semileptonic charge asymmetries. The current experimental uncertainty on semileptonic charge asymmetriesis larger than the tiny central value of the SM expectations, thus allowing plenty of rooms for new physics effects. At the same time, experimental results from the LHCb experiment are eagerly awaited to put some light on this matter. Thus, a new exciting era of B_q^0 meson studies is ahead of us.

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