Lepton Asymmetry in B Decays in the Superweak and in the Standard Theory of CP Violation*

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ABSTRACT

The predictions of the Superweak Theory of CP violation for semileptonic neutral B meson decays are considered. The charge asymmetry in conjunction with the measurements of f_B is seen to be a promising way to distinguish the Superweak from the Standard Theory.

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Telling the Superweak from the Standard Theory explanation would greatly improve our understanding of the observed CP violation. The issue of a Superweak origin of CP violation has been considered by Gerard and Nakada [1] (see also Liu and Wolfenstein [2]) who have shown that a Superweak interaction, mediated by a Higgs-like pseudoscalar, could scale from the Kaon case to give effects in B-decays which may be comparable to those expected in the Standard Theory [3].

From the experimental point of view, the problem has been considered by Weinstein [4], who has pointed out that the predictions of the Superweak (SW) and of the Standard Theory (ST) for the asymmetries in $B^0/\bar{B}^0 \rightarrow J/\psi K_S$ and $B^0/\bar{B}^0 \rightarrow \pi^+\pi^-$, coincide, within three standard deviations, in a considerably large region of the quark mixing parameters. Soares and Wolfenstein [5] have analyzed deviations of SW from ST predictions in a number of other mixing-assisted asymmetries, due to the effect of penguin diagrams.

In this paper, we confront SW to ST predictions for the semileptonic decay asymmetry⁺

$$A_{SL} = \frac{\Gamma(B^0 \rightarrow \ell^+ \nu X^-) - \Gamma(\bar{B}^0 \rightarrow \ell^- \bar{\nu} X^+)}{\Gamma(B^0 \rightarrow \ell^+ \nu X^-) + \Gamma(\bar{B}^0 \rightarrow \ell^- \bar{\nu} X^+)} \quad (1)$$

That the asymmetry (1) may be a good indicator to discriminate SW from ST, can be seen directly from the formula:

$$A_{SL} \simeq \text{Im}\left(\frac{\Gamma_{12}}{M_{12}}\right) \quad (2)$$

In the ST and in the limit of degenerate charm and up quark, $m_c = m_u \simeq 0$, Γ_{12} has the same phase as M_{12} , so that the asymmetry (1) is suppressed [6], [7], [8] by a factor $(m_c/m_b)^2 \simeq 10^{-1}$. Such a suppression, which reflects the more general property that no CP violation may arise when any two quarks are mass degenerate [9] is not present in the SW theory, where Γ_{12} is real, by definition, and the phase of M_{12} is just an independent input parameter, fixed, e.g. by the asymmetry of the $J/\psi K_S$ decay. The situation is made less bright by the fact that another source of suppression may be at work for A_{SL} in the SW theory, related to the sign ambiguity of the $b \rightarrow u$ quark

⁺ For simplicity, we limit the discussion to the decays of a single B^0 or $\bar{B}^0$. The results are trivially extended to the other interesting case of correlated pair decays.

mixing. For a negative value of the mixing we find that the SW prediction is more than one order of magnitude larger than the ST one, and in fact quite sizeable. The positive solution gives, instead, a SW prediction of order 10^{-3} and only a factor of 1.5 larger than the ST one. In the latter case, a discrimination would be still possible if one knew the pseudoscalar decay-constant of the B-meson, f_B , and the value of the heavy quark B-factor. Since the latter can be argued convincingly to be close to unity [10], the present considerations indicate again the crucial importance of a precise determination of f_B , to obtain a sufficiently precise prediction of A_{SL} in the SW and in the ST.

All in all, and even considering the more unfavorable situation, we think that the semileptonic asymmetry offers the cleanest and most realistic signature to distinguish Superweak from Standard Theory in B-decays.

I. Quark Mixing Parameters

We define $B^0 = (\bar{b}d)$ and $CP|B^0\rangle = +|B^0\rangle$. For the Cabibbo-Kobayashi-Maskawa (CKM) [11] mixing matrix we follow the phase convention and the parametrization of ref. [12], for which:

$$U_{us} = \lambda; \quad U_{cb} = A\lambda^2; \quad U_{ub} = A\lambda^3(\rho - i\eta) \quad . \quad (3)$$

For definitiveness, we shall use the numerical values, and errors given in [13]:

$$\lambda = 0.221 \pm 0.002, \quad A = 0.96 \pm 0.09, \quad \sqrt{\rho^2 + \eta^2} = (0.50 \pm 0.14) \quad . \quad (4)$$

Very similar results are obtained in ref. [14]. With the t -quark mass $m_t \simeq 140$, there are two solutions [13] for the complex number $\rho + i\eta$ consistent with the present knowledge of quark decays and $B - \bar{B}$ mixing. One solution is favoured by large values of f_B , ($f_B\sqrt{B} \simeq 225 \text{ MeV}$) and the other by small values ($f_B\sqrt{B} \simeq 125 \text{ MeV}$). Indicatively [13]:

$$\rho \simeq +0.32; \quad \eta \simeq +0.38 \quad (f_B\sqrt{B} \simeq 225 \text{ MeV}) \quad , \quad (5)$$

$$\rho \simeq -0.44; \quad \eta \simeq +0.23 \quad (f_B\sqrt{B} \simeq 125 \text{ MeV}) \quad . \quad (6)$$

In the SW theory, the CKM matrix is of course real orthogonal. We denote by O_{ij} its matrix elements, with:

$$O_{us} = U_{us}; \quad O_{cb} = U_{cb}; \quad O_{ub} = A\lambda^3\sigma \quad , \quad (7)$$

where σ is determined by the $b \rightarrow u$ transition only up to a sign. As in Eq. (4), one finds:

$$\sigma = \pm \frac{|O_{ub}|}{\lambda|O_{cb}|} = \pm(0.50 \pm 0.14) \quad . \quad (8)$$

II. Asymmetries

The asymmetry in the $J/\psi K_S$ channel is defined according to:

$$A(J/\psi K_S) = \frac{\Gamma(B^0 \rightarrow J/\psi K_S) - \Gamma(\overline{B}^0 \rightarrow J/\psi K_S)}{\Gamma(B^0 \rightarrow J/\psi K_S) + \Gamma(\overline{B}^0 \rightarrow J/\psi K_S)} = A_1 \frac{x_d}{1 + x_d^2} \quad , \quad (9)$$

where $x = \Delta m/\Gamma$ is the CP-conserving $B^0 - \overline{B}^0$ mixing parameter. In general, we have

$$A_1 = \text{Im} \left[\frac{p \langle J/\psi K_S | H_W | B^0 \rangle}{q \langle J/\psi K_S | H_W | \overline{B}^0 \rangle} \right] \quad ; \quad (10)$$

with

$$\frac{p}{q} = \sqrt{\frac{M_{12} - \frac{i}{2}\Gamma_{12}}{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}} \quad . \quad (11)$$

In SW theory, A_1 is given by:

$$A_1(SW) = -\sin[\arg(M_{12})] = -\sin\theta_B \quad , \quad (12)$$

and $\sin\theta_B$ is the basic input parameter of the theory.

The same relation holds in the ST, since the transitions $b \rightarrow c$ and $c \rightarrow s$ are purely real in the parametrization given above. The phase of M_{12} is simply related to the CKM parameters because M_{12} is dominated by t-quark exchange:

$$\arg(M_{12}) = \arg(\xi_t^2) = \arg[(U_{tb}U_{td}^*)^2] = \arg[(U_{td}^*)^2] = \sin(2\beta) \quad , \quad (13)$$

and one finds:

$$A_1(ST) = -\sin[\arg(M_{12})] = -\sin(2\beta) \quad . \quad (14)$$

We consider A_1 as a given quantity and will determine the corresponding A_{SL} in SW or in ST (we shall, in addition, assume $A_1 < 0$ since, according to Eq. (14), a positive value would exclude *per se* the Standard Theory).

For the Standard Theory, following the analysis of ref. [8], we obtain:

$$\begin{aligned}
A_{SL}(\text{ST}) &= -C |\xi_t^2| \text{Im} \left[\frac{\xi_u^2(X_{uu} - X_{uc}) + \xi_c^2(X_{cc} - X_{uc}) + \xi_t^2 X_{uc}}{\xi_t^2} \right] \\
&= -C |\xi_t^2| \left[\text{Im} \frac{\xi_u^2}{\xi_t^2} (X_{uu} - X_{uc}) + \text{Im} \frac{\xi_c^2}{\xi_t^2} (X_{cc} - X_{uc}) \right] \\
&\simeq -2CA^2\lambda^6\eta(X_{uu} - X_{uc})
\end{aligned} \tag{15}$$

with

$$\begin{aligned}
C &= \frac{G_F^2 f_B^2 B M_B^3 \tau_B}{4\pi x_d} = 173 \left(\frac{f_B \sqrt{B}}{200 \text{ MeV}} \right)^2 \left(\frac{0.66}{x_d} \right) \\
CA^2\lambda^6 &= 1.9 \cdot 10^{-2} \left(\frac{f_B \sqrt{B}}{200 \text{ MeV}} \right)^2 \left(\frac{0.66}{x_d} \right) \left(\frac{A^2 \lambda^6}{1.1 \cdot 10^{-4}} \right),
\end{aligned} \tag{16}$$

where taking into account the QCD corrections $X_{uu} = 0.920$, $X_{cc} = 0.714$ and $X_{uc} = 0.820$.

The last equality in Eq. (15) follows from the numerical relation: $X_{uu} - X_{uc} \simeq X_{uc} - X_{cc}$. For better comparison with the SW case, we have eliminated $|M_{12}|$ in favour of x_d and τ_B , so that the predicted value of A_{SL} depends explicitly upon $f_B \sqrt{B}$.

The result in Eq. (15) shows explicitly the suppression of A_{SL} , which turns out to be proportional to $X_{uu} - X_{uc}$, in place of the natural scale X_{uu} ($\simeq X_{cc} \simeq X_{uc}$).

In the SW case, Eq. (2) gives:

$$A_{SL}(\text{SW}) = -C \sin \theta_B \left[(\xi_u^{SW})^2 (X_{uu} - X_{uc}) + (\xi_c^{SW})^2 (X_{cc} - X_{uc}) + (\xi_t^{SW})^2 X_{uc} \right] \tag{17}$$

with $(\xi_u^{SW}) = O_{ub} O_{cb}^*$ etc., and X_{uu} etc. the same as above. Simplifying as before, we find:

$$A_{SL}(\text{SW}) = -C \sin \theta_B A^2 \lambda^6 [(1 - \sigma)^2 X_{uc} - (1 - \sigma^2)(X_{uu} - X_{uc})] \tag{18}$$

As anticipated, the scale of A_{SL} is given now by X_{uc} , but it is suppressed by the quark mixing factor, for $\sigma > 0$.

II. Numerical Results

To obtain definite numerical results, we shall use $f_B\sqrt{f_B} = 225 \text{ MeV}$ (125 MeV) for the ST prediction, corresponding to $\rho + i\eta$ in the I quadrant (II quadrant). The same value of f_B will be used for the SW predictions, to maintain the correct ratio. We find:

$$-A_1 = 0.85 \quad -A_{SL}(ST) = 1.9 \cdot 10^{-3} \quad -A_{SL}(SW) = \begin{cases} 35 \cdot 10^{-3} & \text{for } \sigma < 0 \\ 2.5 \cdot 10^{-3} & \text{for } \sigma > 0 \end{cases} \quad (19)$$

for the I quadrant, and:

$$-A_1 = 0.31 \quad -A_{SL}(ST) = 0.35 \cdot 10^{-3} \quad -A_{SL}(SW) = \begin{cases} 4.0 \cdot 10^{-3} & \text{for } \sigma < 0 \\ 0.28 \cdot 10^{-3} & \text{for } \sigma > 0 \end{cases} \quad (20)$$

for the II quadrant.

A more extended illustration of the above results is presented in Figs. 1 and 2. The values of $A_{SL}(SW)$ are plotted vs. $-A_1$, and compared to $A_{SL}(ST)$ with ρ and η restricted to vary on the circle determined by Eq. (4), including estimated errors in the quark mixing parameters. Fig. 1a and 1b correspond to the SW case with $\sigma < 0$, the most favourable one, and Fig. 2a and 2b correspond to the SW case with $\sigma > 0$.

For $\sigma < 0$ the SW prediction is unmistakably larger than the ST one, and at very interesting large values of $|A_{SL}|$. In the $\sigma > 0$ case, we focus on the asymmetries at $-A_1 = 0.85$, as it corresponds to the CKM solution for which the measurements of the $J/\psi K_S$ and $\pi^+\pi^-$ asymmetries are unable [4] to distinguish between SW and ST. The SW result is quite comparable to the ST one and small. However, we think that the 1.4 ratio between the two cases is a reliable prediction, which could be used if we knew the absolute scale of A_{SL} . The largest uncertainty in the scale arises from the value f_B . A minor one comes from the B -factor, for which, however there is convincing evidence [10] that it is close to unity.

In this case, the cleanest way to get the scale of A_{SL} is to normalize it to the branching ratio of the $B^- \rightarrow \tau + \bar{\nu}_\tau$ decay, directly related to f_B . In both ST and SW cases:

$$\begin{aligned} BR_\tau = BR(B^- \rightarrow \tau + \bar{\nu}_\tau) &= \frac{G_F^2 f_B^2 M_B^3 \tau_B}{8\pi} (A^2 \lambda^6) (\rho^2 + \eta^2) \left(\frac{M_\tau}{M_B} \right)^2 \left[1 - \left(\frac{M_\tau}{M_B} \right)^2 \right]^2 \\ &= 1.4 \cdot 10^{-4} \left(\frac{\rho^2 + \eta^2}{0.25} \right) \left(\frac{f_B}{200 \text{ MeV}} \right)^2. \end{aligned} \quad (21)$$

The observation of the asymmetry (20)-(19) and of the branching ratio (21) do not seem too far from the reach of an experiment capable to detect the basic $J/\psi K_S$ asymmetry. In fact, assuming A_1 to be measured within ± 0.03 error, this corresponds to a number of tagged $B^0 \rightarrow J/\psi K_S \rightarrow \ell^+ \ell^- \pi^+ \pi^-$ decays:

$$N[B^0 \rightarrow J/\psi K_S \rightarrow \ell^+ \ell^- \pi^+ \pi^-] \simeq 5.5 \cdot 10^2 . \quad (22)$$

On the basis of branching ratios alone, i.e. without accounting for detection efficiencies, this corresponds to $14 \cdot 10^6$ total number of tagged B^0 decays that is to:

$$\begin{aligned} N[B^0 \rightarrow \ell^+ \nu X^-] &\simeq 2.8 \cdot 10^6 \\ N[B^+ \rightarrow \tau^+ \nu_\tau \rightarrow \ell^+ \nu_\ell \bar{\nu}_\tau \nu_\tau] &\simeq 7 \cdot 10^2 \end{aligned} \quad , \quad (23)$$

i.e. to the statistical errors $\delta A_{SL} \simeq 0.4 \cdot 10^{-3}$ and $\delta BR_\tau \simeq 0.04 \cdot BR_\tau$.

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FIGURE CAPTIONS

Fig. 1 – The charge asymmetry ($-A_{SL}$) vs the J/ψ asymmetry ($-A_1$) in the Superweak Theory with $\sigma < 0$ (dotted line), and in the Standard Theory (full lines). The region inside the full lines gives the ST result consistent with the experimental value of $(\rho^2 + \eta^2)$, with $(\rho + i\eta)$ in the first quadrant and $f_B=225$ MeV (Fig. 1a) or in the second quadrant, and $f_B=125$ MeV (Fig. 1b). The SW curves are computed with the same value of $f_B\sqrt{B}$ for the ST ones. Shaded regions correspond to the best determination of ρ and η , according to refs. [13,14]. In the ST, $-A_1 = \sin 2\beta$. On the ST line, several values of $\delta = \arg(\rho + i\eta)$ are marked, for orientation.

Fig. 2 – Same as in Fig.1, but Superweak Theory with $\sigma > 0$.

Fig. 1

Fig. 2