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CP Violation with Polarized Z^0 •

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ABSTRACT

The forward-backward asymmetry in polarized e^+e^- annihilation at the Z^0 resonance separates particle from antiparticle. This separation facilitates CP violation measurements in neutral B meson decays. The final states of those decays can either be CP eigenstates or not. This note discusses the CP asymmetries expected for the general final state.

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A previous publication[1] pointed out that polarized Z^0s are a powerful tool to separate B^0 from $\overline{B}^0$. Detailed comparison with other "separation" methods showed that indeed the polarized Z^0 method requires the smallest luminosity in e^+e^- collisions for CP violation studies.[2] The efficiency of polarized Z^0 tagging to the study of CP violation was discussed in Ref. 1. The results were valid only for final states which are CP eigenstates. This work extends those results to any final state. As soon as final states that are non CP eigenstates are considered, imperfections in tagging methods may introduce a large distortion to the experimental result.[3] This is a generic problem for all tagging methods known to us. Consider any final state, f, from a neutral B meson. The convention is used that B^0 has $\overline{b}$ content and that $B^0{}_{phys}$ refers to a time evolving B^0 meson. Since f does not have to be a CP eigenstate, two CP asymmetries are defined:

$$\alpha \equiv \frac{\Gamma(B^0{}_{phys}\to f) - \Gamma(\overline{B}^0{}_{phys}\to \overline{f})}{\Gamma(B^0{}_{phys}\to f) + \Gamma(\overline{B}^0{}_{phys}\to \overline{f})}, \tag{1}$$

$$\beta \equiv \frac{\Gamma(B^0{}_{phys}\to \overline{f}) - \Gamma(\overline{B}^0{}_{phys}\to f)}{\Gamma(B^0{}_{phys}\to \overline{f}) + \Gamma(\overline{B}^0{}_{phys}\to f)}. \tag{2}$$

In general, not only the asymmetries but also the rates could differ:

$$\alpha \neq \beta \text{ and}$$

$$\Gamma(B^0{}_{phys}\to f) + \Gamma(\overline{B}^0{}_{phys}\to \overline{f}) \neq \Gamma(B^0{}_{phys}\to \overline{f}) + \Gamma(\overline{B}^0{}_{phys}\to f). \tag{3}$$

One possible parametrization for the four decay rates is:

$$\begin{aligned}
\Gamma(B^0{}_{phys}\to f) &= (1+\alpha)\,T, \\
\Gamma(\overline{B}^0{}_{phys}\to \overline{f}) &= (1-\alpha)\,T, \\
\Gamma(B^0{}_{phys}\to \overline{f}) &= (1+\beta)\,S, \\
\Gamma(\overline{B}^0{}_{phys}\to f) &= (1-\beta)\,S,
\end{aligned} \tag{4}$$

where T and S allow for the difference in rates. In general a, β, S and T can be defined in a time-dependent or time-integrated version.

The Forward-Backward asymmetry is defined as:

$$\mathrm{A,,} \equiv \frac{N(\, b,\ \mathrm{forw}) - N(\, b,\ \mathrm{backw})}{N(\, b,\ \mathrm{forw}) + N(\, b,\ \mathrm{backw})'} \tag{5}$$

Since the dominant process for producing B mesons on the Z^0 is $Z^0 \to b\bar{b}$, we get

$$N(\,\bar{b},\ \mathrm{forw}) = N(\, b,\ \mathrm{backw}), \qquad N(\,\bar{b},\ \mathrm{backw}) = N(\, b,\ \mathrm{forw})\ .$$

The number of decays to final states f in the forward hemisphere is,

$$N(\, f,\ \mathrm{forw}) \sim N(\, b,\ \mathrm{forw})\ 1\text{-}(\,\bar{B}^0{}_{phys} \to f\,) + N(\,\bar{b},\ \mathrm{forw})\ \Gamma(\, B^0{}_{phys} \to f\,)\ .$$

An analogous formula holds for the number of CP conjugated final states, $\bar{f}$, in the backward hemisphere. The observable CP violation parameter defined as

$$A_{CP}^{meas}(\, f) \equiv \frac{N(\, f,\ \mathrm{forw}) - N(\,\bar{f},\ \mathrm{backw})}{N(\, f,\ \mathrm{forw}) + N(\,\bar{f},\ \mathrm{backw})}\ , \tag{6}$$

becomes

$$A_{CP}^{meas}(\, f) = \frac{\alpha\, T - \beta\, S - A_{FB}\,(\,\alpha\, T + \beta\, S\,)}{T + S + A_{FB}\,(\, S - T\,)}\ . \tag{7}$$

The asymmetry a, defined in Eq. (1), corresponds to A_{CP} in Ref. 1. For f, an eigenstate of CP,[4] $\alpha = \beta$ and T = S; consequently $A_{CP}^{meas} = -$ a A,,. Eq. (4) of Ref. 1,

$$A_{CP}^{meas} = A_{CP}\ A_{FB}\ ,$$

differs from the present result by an overall minus sign, because the convention where B^0 has $\bar{b}$ quark content was used inconsistently.5 Using the convention outlined above, if $A_{FB} = 1$, then only b quarks (hadronizing into $\bar{B}^0{}_{phys}$) occur in the forward hemisphere. The asymmetry, A_{CP}^{meas}, then measures -a. For a general final state that is not necessarily a CP eigenstate, Eq. (7) replaces Eq. (4) in Ref. 1.

Lepton asymmetry

Consider the semileptonic decay modes of the neutral B-meson, $\ell^{\pm}$ + X, denoted hereafter as $\ell^{\pm}$. A pure B^0 does not decay into the wrong sign lepton, ℓ^-. The situation changes when the B^0 time-evolves. Time-dependent rates for B mesons into semileptonic decays can be calculated. For time-integrated B mesons, the semileptonic decays are:[6]

$$\Gamma(B^0_{phys} \rightarrow \ell^-) \sim Br(\bar{B}^0 \rightarrow \ell^-)\ \frac{x^2}{2\ (1\ +\ x^2)} \left|\frac{q}{p}\right|^2, \tag{8}$$

$$\Gamma(\bar{B}^0_{phys} \rightarrow \ell^+) \sim Br(B^0 \rightarrow \ell^+)\ \frac{x^2}{2\ (1\ +\ x^2)} \left|\frac{p}{q}\right|^2, \tag{9}$$

$$\Gamma(B^0_{phys} \rightarrow \ell^+) = \Gamma(\bar{B}^0_{phys} \rightarrow \ell^-) \sim Br(B^0 \rightarrow \ell^+)\ \frac{2\ +\ x^2}{2\ (1\ +\ x^2)}\ . \tag{10}$$

Here $Br(B^0 \rightarrow \ell^+)$ [= $Br(\bar{B}^0 \rightarrow \ell^-)$] is the semileptonic branching ratio of a pure B^0 meson, $x \equiv (Am/y)_{B^0}$ which is the mixing parameter, and p and q are coefficients of the light and heavy neutral B mesons.[4] Identify the final statef with the semileptonic decay mode ℓ^- + X. In general, the wrong sign lepton asymmetry is different from zero, $\alpha = (|q/p|^2 - |p/q|^2) / (|q/p|^2 + |p/q|^2) \neq 0$, whereas the right sign asymmetry is zero, β = 0.6 Since the final state is not a CP eigenstate, two measurable CP violating asymmetries exist. In the limit of small $\alpha << 1$,

$$A^{meas}_{CP}(f = \ell^-) \approx \frac{\alpha\, x^2\, (1\ -\ A_{FB})}{2\ +\ 2x^2\ +\ 2A_{FB}}\ , \tag{11}$$

and

$$A^{meas}_{CP}(\bar{f} = \ell^+) \approx \frac{-\,\alpha\, x^2\, (1\ +\ A_{FB})}{2\ +\ 2x^2\ -\ 2A_{FB}}\ . \tag{12}$$

We note in passing that for the 3 x 3 Kobayashi Maskawa[7] model the asymmetry a is predicted to be tiny,* and the above two equations hold. Even if we could separate the semileptonic decays of the neutral B_d mesons from the other $\bar{b}$ flavored hadrons, the observable wrong sign lepton asymmetry will be suppressed by a factor smaller than A_{FB}. For B_d mesons where x ≈ 0.72, and with 90% polarized electrons where $A_{FB} = 0.75$,[9] we obtain

$$A_{CP}^{meas}(\ell^+) \approx -0.59\ cc\ , \qquad A_{CP}^{meas}(\ell^-) \approx 0.029\ \alpha\ . \qquad (13)$$

Of course, in inclusive semileptonic decays the flavor of the-parent B meson cannot be established. If, in addition, other backgrounds-such as cascade decays $(b \to c \to \ell^-)$, predicted $B_s\ \overline{B}_s$ mixing effects, and falsely identified, non-prompt leptons-are included, the asymmetry is further diluted to $A_{CP}^{meas}(\ell^+) \approx -0.13\ \alpha$.[1] It is important to realize that the dilution occurring with the FB-tag, when the final state is not a CP eigenstate, is a generic problem common to all the tagging schemes known to us.

For the unpolarized case with $A_{FB} = 0.86$. $A^o_{FB} = 0.13$, the observable B_d-asymmetries are $A_{CP}^{meas}(\ell^+) = -0.21$ a, and $A_{CP}^{meas}(\ell^-) = +0.14$ a. They are about three times smaller than $A_{CP}^{meas}(\ell^+) \approx -0.59$ cx with a 90% polarized e^- beam. This apparent gain is somewhat cancelled by the fact that $A_{CP}^{meas}(\ell^+)$ measures mainly the wrong sign lepton decays of B_d and those occur less frequently.

REFERENCES

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[2] G. J. Feldman et al., SLAC report, SLAC-PUB-4838, Jan. 1989, contribution to DPF Summer study, Snowmass '88, High Energy Physics in the 1990's, Snowmass, CO, June 27-July 15, 1988.

[3] The only case considered in Ref. 1 where the final state is not a CP eigenstate is the semileptonic asymmetry. There the results came from an explicit numerical calculation taking wrong tagging probabilities correctly into account.

[4] For a review see, for instance, I. I. Y. Bigi and A. I. Sanda, Nucl. Phys. 8281, 41 (1987) and references therein.

[5] The inconsistent use of sign does not have any effect on the reported numbers in Ref. 1.

[6] A. Pais and S. B. Treiman, Phys. Rev. D12, 2744 (1975); J. S. Hagelin, Nucl. Phys 8193, 123 (1981); Bigi and Sanda, Ref. 4.

[7] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. 49,652 (1973).

[8] T. Aitomari, L. Wolfenstein and J. D. Bjorken, Phys. Rev. D37, 1860 (1988).

[9] The Forward-Backward asymmetry, A_{FB}, is integrated over $0.3 < |\cos\theta| < 0.9$.