SLAC – PUB – 4544
June 1988
(E/T)

CP Violation at the Z^0 with Polarized Beams*

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ABSTRACT

The forward-backward asymmetry in e^+e^- annihilation induced by neutral currents allows an effective particle-antiparticle separation. This is used to define a simple CP violating observable. At the Z^0-resonance, where the production rates are high, polarized electrons may increase the forward-backward asymmetries by up to a factor six. The number of events necessary to establish a CP-violating effect with neutral B mesons is reduced by about an order of magnitude compared with the usual lepton tag method.

Submitted to *Physics Letters B*

⋆ Work supported in part by the Department of Energy, contract DE-AC03-76F00515.

1. Introduction

So far, the only observed evidence for CP violation has come from the kaon system.[1] Since no deep understanding of the origin of CP violation in nature exists, new experimental information is desirable. The KM model attempts to relate the problem of CP violation to the existence of particle generations.[2] In that model, information about CP violation in heavy quark systems is of particular interest, and there is some hope for measurable effects in B-meson decays.[3]

Consider a final state f into which either a B^0 or a $\overline{B}^0$ can decay. Interfering amplitudes can lead to CP-violating effects,[3]

$$A_{\rm CP} \equiv \frac{\Gamma(B^0_{\rm phys} \to f) - \Gamma(\overline{B}^0_{\rm phys} \to \overline{f})}{\Gamma(B^0_{\rm phys} \to f) + \Gamma(\overline{B}^0_{\rm phys} \to \overline{f})} \quad . \tag{1}$$

The $B^0_{\rm phys}$ denotes the physical (i.e. time evolved) initially pure B^0. At later times $B^0_{\rm phys}$ has a nonvanishing probability of being a B^0 or $\overline{B}^0$. The Kobayashi–Maskawa (KM) model[2] with three generations of quarks predicts large asymmetries for some exclusive nonleptonic modes, and tiny wrong sign, semileptonic asymmetries [defined in Eq. (12)]. After the recent ARGUS result[4] on B_d mixing some exclusive nonleptonic B_d modes look promising. To measure these asymmetries, it is crucial to distinguish whether the initial beauty meson was a particle (B^0) or an antiparticle ($\overline{B}^0$).† We refer to this as the tagging requirement. The purpose of this note is to propose that polarized electron beams on the Z^0-pole[5-7] can yield a clean separation between particle and antiparticle.

The usual technique of particle-antiparticle separation, however, assumes associated quark production. By measuring a property of one of the particles, the identity of the other particle can be inferred. Examples of such a tagging technique include the charge of a lepton inside a jet or reconstruction of the jet-charge. Normally these tagging methods can only be applied to a small subset of events. In a real experimental situation, the particle-antiparticle separation is diluted because of background and mixing contributions. This dilution will be discussed later on in more detail.

We propose the use of polarized electron beams on the Z^0−pole as an alternative. This provides a simple way to separate particles from antiparticles by

† The B^0 contains a $\bar{b}$ quark.

detector hemispheres, which we call Forward-Backward (FB) tagging. Then the following asymmetry tests for CP violation:

$$A_{\rm CP}^{\rm meas} = \frac{N(f, \text{forw}) - N(\overline{f}, \text{backw})}{N(f, \text{forw}) + N(\overline{f}, \text{backw})} \quad . \tag{2}$$

Here, $N(f, \text{forw})$ is the number of decays into the final state in the forward hemisphere and $N(\overline{f}, \text{backw})$ is the number of charge-conjugated decays in the backward hemisphere. As examples, one can measure the number of neutral B_d–meson decays into $J/\psi\ K_s^0$ separately in the forward and backward hemispheres, or the number of μ^-'s in the forward hemisphere and the number of μ^+'s in the backward hemisphere. One could also measure the number of K_s^0's, γ's or D^0's and their charge conjugates separately in the two detector hemispheres. Although some of these asymmetries are predicted to be very small, the simplicity and generality of the method makes it an attractive way to study CP violation.

The asymmetry $A_{\rm CP}^{\rm meas}$ is different from the forward-backward charge asymmetry, $A_{\rm FB}$, commonly used in neutral current studies. There one measures

$$A_{\rm FB} = \frac{N(b, \text{forw}) - N(b, \text{backw})}{N(b, \text{forw}) + N(b, \text{backw})} \quad , \tag{3}$$

where b denotes the beauty quark. In the absence of CP violation, $A_{\rm CP}^{\rm meas}$ vanishes, but $A_{\rm FB}$ can still be nonzero and large.

If there is a sizeable asymmetry $A_{\rm FB}$ due to neutral current effects, the particle-antiparticle content in the two hemispheres of the detector is unequal. Then $A_{\rm CP}^{\rm meas}$ measures the product of the CP asymmetry and the effectiveness of the experimental particle-antiparticle separation, hence

$$A_{\rm CP}^{\rm meas} = A_{\rm CP} \cdot A_{\rm FB} \quad . \tag{4}$$

It is well known that the neutral current couplings of the Z^0 cause an asymmetry $A_{\rm FB}$ in fermion pair production. Unfortunately, at the Z^0-resonance, where the cross section is high, $A_{\rm FB}$ is expected to be rather small. But with polarized beams at an e^+e^- collider, $A_{\rm FB}$ at the Z^0-peak can be greatly enhanced. *Polarized beams are a simple, experimentally appealing and statistically powerful method of separating particles and antiparticles.*

Section 2 discusses the cross section and $A_{\rm FB}$ in e^+e^- annihilation into fermions. Section 3 compares quantitatively Forward-Backward tagging (FB tagging) with lepton tagging to separate particles from antiparticles in $b\bar{b}$ events. In Section 4, a few examples are given to illustrate the luminosity required to measure $A_{\rm CP}$ at the Z^0.

2. Cross Section and Forward–Backward Asymmetries at the Z^0

The cross section for $e^+e^- \to b\bar{b}$ is expected to be largest at the Z^0-resonance; including radiative corrections one expects 5 nb. The measured cross section at the $\Upsilon(4s)$ is about 1 nb.[8] In the continuum between the $\Upsilon(4s)$ and the Z^0 the cross section is substantially smaller: about 0.1 nb at $E_{\mathrm{cm}} = 15$ GeV and 0.01 nb at $E_{\mathrm{cm}} = 60$ GeV.

The differential cross section for fermion pair production in e^+e^- annihilation is

$$\frac{d\sigma}{d\Omega} = \sigma_0 \cdot (1 + \cos^2\theta + 2A^0_{\mathrm{FB}}\cos\theta) \quad . \tag{5}$$

Here, A^0_{FB} is the forward-backward asymmetry in the very forward direction, $\cos\theta = 1$, whereas A_{FB} is integrated over the geometrical acceptance. In the continuum, A_{FB} is induced by interference between the one photon and the Z^0 annihilation amplitudes. At $E_{\mathrm{cm}} \sim 60$ GeV this effect can be large, but the cross section for $b\bar{b}$ production is small.

At the Z^0-resonance, the forward-backward asymmetry is generated by the different couplings of the Z^0 to left- and right-handed fermions and is given by

$$A^0_{\mathrm{FB}} = A^e_{\mathrm{LR}} \cdot A^f_{\mathrm{LR}} \quad . \tag{6}$$

Here A^e_{LR} (A^f_{LR}) is the left-right asymmetry for the coupling of the electron (final state fermion f) to the Z^0.

If we take $\sin^2\theta_w = 0.23$, as measured in various neutral current phenomena,[9] we expect the following values: $A^e_{\mathrm{LR}} = 0.16$, $A^c_{\mathrm{LR}} = 0.66$ and $A^b_{\mathrm{LR}} = 0.94$. Because of the small value of A^e_{LR}, we expect a small forward-backward asymmetry in fermion pair production at the Z^0.

With polarized beams, the forward-backward asymmetry can be directly manipulated in the experiment.[6] The plans for electron polarization at SLC are well advanced. Polarization of 45% is expected for the initial running, and research is being pursued to increase it to 90%.[6] Similarly high polarization at LEP seems possible and studies are under way.[10] One can introduce a modified left-right asymmetry which takes the initial electron polarization (P_e) into account, and replaces A^e_{LR} in Eq.(6) by:

$$\tilde{A}^e_{\mathrm{LR}} = \frac{A^e_{\mathrm{LR}} + P_e}{1 + A^e_{\mathrm{LR}} \cdot P_e} \quad . \tag{7}$$

Assuming $\sin^2\theta_w = 0.23$, $\tilde{A}^e_{\mathrm{LR}}$ will increase to 0.93(0.57) for 90% (45%) polarization. Therefore, with polarized beams we expect a sizeable forward-backward asymmetry for quark pair production: with $P_e = 90\%(45\%)$, we expect $A_{\mathrm{FB}}^0 = 0.87(0.54)$ for the b-quark [for c-quarks, $A_{\mathrm{FB}}^0 = 0.61(0.38)$].

3. Comparison of Methods to Separate Particles from Antiparticles

All experimental methods to separate particles and antiparticles are imperfect. In analogy to A_{FB}, we define a 'separation asymmetry':

$$A_{\mathrm{sep}} = \frac{N_{\mathrm{correct}} - N_{\mathrm{wrong}}}{N_{\mathrm{correct}} + N_{\mathrm{wrong}}} \quad , \tag{8}$$

where the subscripts *correct* and *wrong* refer to correctly and wrongly tagged particles. The resulting 'separation asymmetry' will play an equivalent role to A_{FB} in Eq.(4). The number of $b\bar{b}$ events ($N_{b\bar{b}}$) necessary to establish a CP asymmetry, A_{CP}, of N_σ standard deviations is given by

$$N_{b\bar{b}} = \frac{N_\sigma^2}{A_{\mathrm{CP}}^2 \cdot A_{\mathrm{sep}}^2} \, \frac{1}{2BR(B^0 \to f)} \, \frac{1}{\epsilon_f} \, \frac{1}{\epsilon_{\mathrm{tag}}} \, \frac{1}{\sigma_{B^0}} \quad , \tag{9}$$

where ϵ_{tag} is the efficiency for the particle-antiparticle tagging method, $\mathrm{BR}(B^0 \to f)$ is the expected (or measured) branching ratio of the pure B^0 into the CP eigenstate* f and ϵ_f is the reconstruction efficiency for that final state f. σ_{B^0} denotes the probability that a beauty quark hadronizes into the neutral B-meson and we assume the relative hadronization rates

$$\sigma_{B_d} : \sigma_{B_u} : \sigma_{B_s} : \sigma_{B_{\mathrm{baryon}}} = 0.35 : 0.35 : 0.15 : 0.15 \quad . \tag{10}$$

To study the effectiveness of different tagging methods we define a quality factor

$$Q_{\mathrm{sep}} = A_{\mathrm{sep}}^2 \cdot \epsilon_{\mathrm{tag}} \quad . \tag{11}$$

This quality factor takes the tagging efficiency and the dilution of the particle-antiparticle separation into account [see Eq. (9)]. In Table 1 we compare Q_{sep} for three different methods: Gedanken tagging (i.e., perfect separation of particles and antiparticles), lepton tagging (as in present B-meson studies) and Forward-Backward tagging (FB tagging) at the Z^0-resonance with unpolarized and polarized beams.

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* If f is not a CP eigenstate, then 2 $\mathrm{BR}(B^0 \to f)$ has to be replaced by $[\mathrm{BR}(B^0_{\mathrm{phys}} \to f) + \mathrm{BR}(\overline{B}^0_{\mathrm{phys}} \to \overline{f})]$.

Gedanken tagging assumes 100% efficiency and 100% separation, hence $Q_{\rm sep} = 1$. We now show that by comparison lepton tagging requires 33 times more events to achieve the same precision, while FB tagging (with 90% polarization) requires only three times more events.

In B-meson studies one can separate particles and antiparticles by using the charge of the lepton. By this method only those events can be used where a b-quark or $\bar{b}$-quark decays into an electron or muon. In addition, there are severe sources of false charge assignments which will decrease $A_{\rm sep}$. In particular, in $b\bar{b}$ events the cascade decays ($b \to c \to l$), $B^0 - \overline{B}^0$ mixing effects, and falsely identified, nonprompt leptons result in wrong sign leptons and degrade $A_{\rm sep}$.

In order to limit the cascade background and other backgrounds from nonprompt leptons, the usual method is to require a minimum momentum (p) and a minimum transverse momentum (p_t) of the lepton relative to the jet axis.[11] For $b\bar{b}$ production at the Z^0-pole, by requiring $p > 2$ GeV and $p_t > 1$ GeV and by applying other commonly used electron and muon identification criteria,[11] one typically detects 10% of the b decays. Those are direct decays of b quarks into leptons. The total semileptonic branching ratio for all the beauty flavored hadrons was taken to be a quarter. With respect to the real direct lepton signal, there is an additional 25% from background contamination: 15% from charm cascades and 10% from nonprompt lepton misidentification. With these numbers, $A_{\rm sep}$ is reduced to 68% and $\epsilon_{\rm tag} = 0.125$. Therefore, compared to a Gedanken experiment, the lepton tagging method achieves at most $Q_{\rm sep} = 0.06$. Taking into account the measured mixing for B_d[4] [Probability ($B_{d,\rm phys} \to \overline{B}_d$) $\approx$ 17%],† and expected mixing for B_s [Probability($B_{s,\rm phys} \to \overline{B}_s$) $\approx$ 50%], and assuming a relative hadronization ratio as in Eq.(10), $A_{\rm sep}$ will be further degraded by about a factor of 0.73.* We expect an overall $A_{\rm sep} \sim$ 50% and $Q_{sep} \sim 0.03$. Therefore, compared to Gedanken tagging one needs about 33 times more events to establish the same effect. The precise values of $Q_{\rm sep}$ depend on the details of the experimental detector and the input parameters to the Monte Carlo simulation.

We compare these numbers with those from the published dilepton studies of ARGUS,[4] CLEO[12] and two PEP experiments.[13] The raw numbers of same and opposite sign dileptons include all the effects which happen in a real experiment,

† We define Probability ($B^0_{\rm phys} \to \overline{B}^0$) $\equiv x^2/[2(1+x^2)]$, where $x \equiv \Delta m/\gamma$. Here CP violation is neglected ($|q/p| = 1$).

* Among the beauty flavored and anti-beauty flavored hadrons a few are $B^0 - \overline{B}^0$ pairs. Those neutral particle-antiparticle pairs, $B^0 - \overline{B}^0$, were assumed to be in an incoherent configuration. That is to say, the charge-conjugated even and odd configurations were assumed to be equal.

and they are a reasonable indicator of what can actually be achieved. ARGUS observes 351 dilepton events out of 88,000 Υ(4s) events; 301 opposite sign‡ and 50 same sign dilepton events are found. Their numbers correspond to $A_{sep}= 0.85$ and $\epsilon_{tag}= 0.063$ for a lepton tag of a hadronic B-meson decay. For the ARGUS experiment we derive a quality factor of $Q_{sep} = 0.045$. CLEO observes 158 events with $A_{sep} = 0.85$ and $\epsilon_{tag}= 0.043$, while the PEP experiments achieved $A_{sep} = 0.55$ and $\epsilon_{tag} = 0.036$. Therefore, CLEO achieves $Q_{sep} = 0.03$, and for the PEP experiments $Q_{sep} = 0.01$. The $\Upsilon(4s)$ experiments (ARGUS and CLEO) benefit from suppressed backgrounds, since they are in a kinematically favored situation and the overall mixing is expected to be smaller at the $\Upsilon(4s)$.♮ The PEP results are worse compared to our estimate of Q_{sep} at the Z^0, because lepton identification was only partially available in those detectors.

In the case of particle-antiparticle separation into hemispheres (FB tagging) the geometrical acceptance and the magnitude of the forward-backward asymmetry has to be taken into account. Since the forward-backward asymmetry and the cross section are largest at small angles relative to the beam axis, good coverage for particle detection down to small angles is important.

If we integrate the events from $\cos\theta = 0.3$ to $\cos\theta = 0.9$, 63% of the cross section remains ($\epsilon_{tag}= 0.63$). Compared to the forward-backward asymmetry in the very forward direction, $A^0_{\rm FB}$, the asymmetry, $A_{\rm FB}$, is then reduced by 0.86. Therefore, even if $A^0_{\rm FB}$ is 100%, $Q_{sep} = 0.46$. In Table 1 we show the values for $A_{\rm FB}$ denoted as A_{sep}, which can be achieved for various degrees of incident electron beam polarizations. Compared to the lepton tagging method, the FB tagging gains in statistics by about an order of magnitude.

A conceivable background to FB tagging is the process $Z^0 \rightarrow t\bar{t}$, if the top mass is light enough. With present limits on the top mass,[14] t–quarks from Z^0decays will lead to spherical event topologies, and can be easily removed.

‡ We include all opposite sign candidates, the first row of Table 2 in Ref. 4.

♮ This is due to the quantum correlation between the two neutral B's. Also the resonance is below the $B_s - \bar{B}_s$ pair threshold.

4. CP Violation in Neutral B-Mesons

A few promising nonleptonic decay modes are $B_d \to D^- D^+$, $B_d \to D^- D^{*+} + c.c.$, $B_d \to p\overline{p}$, and $B_d \to J/\psi\, K^0_s$. We now give some crude estimates of required $b\overline{b}$ event samples necessary to observe the predicted CP asymmetries. To that end, Table II furnishes the predicted asymmetry,[15] the branching ratio, and the detection efficiency of those final states. Using Eq. (9),* the last three columns of Table II then give estimates of the required number of $b\overline{b}$ events to establish 3σ effects for three cases: (a) Gedanken tagging, (b) lepton tagging, and (c) FB tagging (90% polarization).

A few remarks about the table are in order. First, the branching ratio of $B_d \to J/\psi\, K^0_s$ can be estimated from the observed charged $B^-_u \to J/\psi\, K^-$ decay. Estimated branching ratios into $D^- D^+$, $D^- D^{*+} + c.c.$, $p\overline{p}$ are more uncertain. The reconstruction efficiencies times branching ratios of J/ψ decaying into lepton pairs, $\epsilon_{J/\psi}$, is about 10%. The K^0_s can be seen in the charged dipion mode and is about $\epsilon_{K^0_s} \sim 40\%$. For D-mesons, we estimate $\epsilon_{D^+} \sim 5\%$, $\epsilon_{D^{*+}} \sim 10\%$. For the decay $B_d \to p\overline{p}$, we assume that lifetime and momentum cuts have to be applied, resulting in $\epsilon_{p\overline{p}} \sim 30\%$. The $p\overline{p}$ mode has both a CP even and odd piece. The asymmetry of the even piece is opposite the odd one. Thus, the $B_d \to p\overline{p}$ asymmetry is rather uncertain, but potentially large if one piece dominates.

All the listed decay modes are rarely seen—that is, the branching ratio times detection efficiency is tiny ($\sim 10^{-5}$). Although the asymmetries could be large, the tiny fraction of detected events ($\sim 10^{-5}$) increases the required number of $b\overline{b}$ events to at least 10^7, even with Gedanken tagging. The tagging imperfections, as discussed in previous sections, increase the required number of $b\overline{b}$ events by another factor of about 30 for lepton tagging, but by only a factor of three for the FB tagging (90% polarization).

Finally, we wish to address the "wrong sign" semileptonic asymmetry,

$$A_{CP} = \frac{\Gamma(B^0_{\rm phys} \to \ell^-) - \Gamma(\overline{B}^0_{\rm phys} \to \ell^+)}{\Gamma(B^0_{\rm phys} \to \ell^-) + \Gamma(\overline{B}^0_{\rm phys} \to \ell^+)} \, . \qquad (12)$$

This asymmetry requires tagging. The common method is to measure the same sign dilepton asymmetry,

$$A_{\ell\ell} = \frac{N^{--} - N^{++}}{N^{--} + N^{++}} \, . \qquad (13)$$

⋆ The quality of separation can be found in Table I.

Here N^{--} (N^{++}) is the number of events with two positive (negative) charged direct leptons and there is no distinction between the "tagging lepton" and the "signal lepton."

FB tagging makes the additional lepton superfluous. Given a large FB asymmetry, we propose to probe the "wrong sign" semileptonic asymmetry via Eq. (2),

$$A_{CP}^{\text{meas}} = \frac{N(\ell^-, \text{backw}) - N(\ell^+, \text{forw})}{N(\ell^-, \text{backw}) + N(\ell^+, \text{forw})} \ . \tag{14}$$

Assuming an A_{FB} of 0.75 for the b quarks, and the same background factors from cascade decays and nonprompt leptons as in Section 3, one expects† a dilution factor of about eight,

$$A_{CP}^{\text{meas}} \approx 0.13 \ A_{CP} \ .$$

A detailed calculation shows that slightly less dilution is expected for the (same sign) dilepton asymmetry,

$$A_{\ell\ell} \approx 0.18 \ A_{CP} \ .$$

Even though the resulting asymmetries for both tagging schemes are about equal, the additional lepton in the dilepton asymmetry increases the required number of $b\bar{b}$ events by about half an order of magnitude compared to FB tagging. The statistical error on the "wrong sign" semileptonic asymmetry, Eq. (12), is estimated to be

$$\Delta A_{CP} \approx \frac{0.035(0.072)}{\sqrt{N_{b\bar{b}}/10^6}} \ , \tag{15}$$

where 0.035 is the value to be used for the FB tagging, and 0.072 for the same sign dilepton method. Thus, FB tagging requires 1×10^7 $b\bar{b}$ events to observe a "wrong sign" semileptonic asymmetry (Eq. (12)) of 0.01 (to 1σ accuracy), whereas the dilepton method requires 5×10^7 events. The value of 0.01 is an upper limit within the KM model.[16]

There is an additional advantage to FB tagging. To get a handle on systematic errors in the detection efficiency of the leptons, one could look at the right

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† We assumed for the background calculation that 1/2 of the nonprompt leptons originate from π, K decays, and γ conversions. The other 1/2 arises from primary $c\bar{c}$ production on the Z^0. This latter half is unevenly divided between the forward and backward hemispheres due to the initial polarization of the electrons.

sign semileptonic asymmetry,* which is predicted to be much smaller than the wrong sign one. Thus, for FB tagging an additional experimental cross-check exists on this source of systematic error.

We have not discussed B_s decays in this paper even though large CP violations are expected. In order to observe CP violation with B_s mesons, time dependent studies of their decays are required due to the large expected mixing.[3] The Z^0 resonance is a natural place to study time dependent effects of B_s and B_d mesons, due to the large boost given to B mesons produced there. We also note that B_s mesons have a higher production cross section at the Z^0 resonance by at least an order of magnitude than anywhere else at e^+e^- colliders.

5. Summary

An e^+e^- collider at the Z^0 resonance with polarized beams can significantly enhance the experimental sensitivity to CP violation. The large forward-backward asymmetry offers a powerful tool to separate particles from antiparticles. A study of various promising examples shows that with an integrated luminosity of 10^{40} cm^{-2}, an e^+e^- collider with polarized beams will be able to measure CP violation induced by the KM mechanism.

6. Acknowledgements

We are grateful to the SLC polarization group at SLAC for encouragement and stimulating discussions. We thank Josh Frieman, Fred Gilman and Chris Wendt for comments on the manuscript.

* The asymmetry that is obtained under the interchange of $\ell^- \leftrightarrow \ell^+$ in Eq. (14).

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Table 1. Comparison of various methods to separate particle and antiparticle.

Method	A_{sep}	ϵ_{tag}	Q_{sep}	$N_{b\bar{b}}^{equiv}$
Gedanken Experiment	1.0	1.0	1.0	1
Lepton tag	0.50	0.12	0.03	33
FB - tag (no pol.)	0.13	0.63	0.01	100
FB - tag (45% pol.)	0.46	0.63	0.13	8
FB - tag (90% pol.)	0.75	0.63	0.35	3

Table 2. Rate estimate for various decay modes to observe an asymmetry.

Decay	BR($B \to f$)	$\lvert A_{CP} \rvert$	ϵ_f	$N_{b\bar{b}}$(Gedanken)	$N_{b\bar{b}}$(Lepton)	$N_{b\bar{b}}$(90% pol.)
$B_d \to J/\psi\ K_s^0$	$5.0 \cdot 10^{-4}$	0.20	0.04	$1.6 \cdot 10^7$	$5.3 \cdot 10^8$	$4.5 \cdot 10^7$
$B_d \to D^+ D^-$	$1.0 \cdot 10^{-3}$	0.20	0.003	$1.1 \cdot 10^8$	$3.5 \cdot 10^9$	$3.0 \cdot 10^8$
$B_d \to D^{*+} D^-$ +h.c.	$5.0 \cdot 10^{-3}$	0.20	0.005	$1.3 \cdot 10^7$	$4.2 \cdot 10^8$	$3.6 \cdot 10^7$
$B_d \to P\overline{P}$	$5.0 \cdot 10^{-5}$	0.3	0.3	$9.5 \cdot 10^6$	$3.1 \cdot 10^8$	$2.7 \cdot 10^7$