PROCEEDINGS OF SCIENCE

CP violation in the three-body $B^{\pm}$ phase-space

J.H. Alvarenga Nogueira*†, T. Frederico
Instituto Tecnológico de Aeronáutica, 12228-900, São José dos Campos, SP, Brazil
E-mail: jhan@ita.br, tobias@ita.br

I. Bediaga, P.C. Magalhães
Centro Brasileiro de Pesquisas Físicas, 22290-180, Rio de Janeiro, RJ, Brazil
E-mail: bediaga@cbpf.br, pmagalhaes@cbpf.br

In this contribution, we briefly review the literature regarding Charge-Parity Violation (CPV) in two- and three-body decays, with emphasis in the contribution of soft final state interactions. We describe a model based on the CPT constraint including final state interactions, which can be applied to study CPV in the high two-body invariant mass region. The CPV in this sector of the phase space could be associated with the final state interaction coupling a pair of light pseudoscalars to double-charm B decay channels. Furthermore, we discuss the applicability of this idea to analyse CPV data from B decays in three light pseudoscalars for two-body invariant mass around 4 GeV, considering final state interactions and the CPT constraint.

38th International Conference on High Energy Physics
August 3-10, 2016
Chicago, USA

*Speaker.

†J.H.A.N. acknowledges the support of Grant #2014/19094-8 from Fundação de Amparo à Pesquisa do Estado de São Paulo, the grant from the 2015 American Physical Society (APS) - Brazilian Physical Society (SBF) interchange program and the ICHEP 2016 organizing committee for the partial financial support.

PoS(ICHEP2016)635

1. Introduction

Two-body B decays are largely explored in the literature, while three-body ones are still a big challenge. Considering the $2+1$ factorization we can use the properties of two-body decays to understand three-body decays, neglecting three-body rescattering effects. This is not the best scenario, since it is well known that the dynamics in three-body decays is much more complex than in the two-body case. If soft final state interactions (FSI) are important for specific two-body decays, we can believe that it will contribute to three-body decays which involves the same mesons in the final state. This occurs since the B meson energy will be more distributed among the pair of mesons and the bachelor particle, which interacts with the others. Here we present several examples and discussions from the literature that gives a consistent support to FSI of the type $DD' \to PP'$, where D and D' are charmed mesons, and P and P' are light pseudoscalars, like kaon or pion.

Already in the seminal Bander-Silverman-Soni (BSS) paper [1], where the first mechanism allowing CPV in charged states was presented, the discussion involving $c\bar{c}$ intermediate states in the process $b \to c\bar{c}s \to u\bar{u}s$ appears with fundamental importance for the CPV, since it contributes to the strong phase (absorptive part) of the loop penguin diagrams. This quark-level process can have a counterpart in low-energy hadronic FSI's, where the $c\bar{c}$ pair would be understood as a double charm meson intermediate rescattering contribution. This inelastic transition generates the necessary coupling between channels to allow CPV with the constraint of CPT. The mechanism by BSS was not taking into account carefully the CPT constraint, which was later properly introduced [2]. That study was treating the charm quark mass m_c as a free parameter to check when a new intermediate channel, for example $b \to sc\bar{c}$, opens allowing an absorptive part arising from the timelike gluon propagator, where the internal legs goes on-shell for $q^2 > m_c^2$ [3]. We reinforce that these examples are not exhaustive and illustrate situations where we can find evidences of soft FSI's, which can be also associated with the $DD' \to PP'$ transitions.

It is possible that the effects from the penguin absorptive parts (hard FSI) get washed out by soft FSI in two-body modes, and this opens the possibility of soft FSI as an important role in the decay process. In this case, is even more complicated to understand exclusive partial rate asymmetries, since these inelastic phase-shifts are extremely difficult to measure [2]. The first paper calling the attention to CPV coming from hadronic FSI's in B meson decays, was the one by Wolfenstein, in 1991 [4]. The idea was to perform a partial wave decomposition of the scattering amplitude of the final state and take into account the strong phase shifts in the the weak decay amplitude. Other important feature of that formalism is the conservation of CPT, which is easily lost in the BSS approach. This type of analysis was applied for B meson three-body decays and compared with CPV data in Refs. [5, 6]. There, using a parametrized S-matrix from the $\pi\pi$ scattering data to compute the inelastic transition $\pi\pi \to KK$, it was possible to understand the CPV distribution in the low two-body invariant mass region of the phase space.

Transitions with double charm mesons as $D\bar{D} \to PP$, where P is a pion or kaon in the $B \to PPP$ decay, can couple different decay channels by the strong force. This coupling between two-body channels induces CPV above the $D\bar{D}$ threshold, which is the region of large two-body invariant masses in the B meson phase space. This region presents a considerable amount of CP asymmetry for $B \to PPP$ decays [7]. However, inelastic transitions like $D\bar{D} \to PP$ effects in three body decays are not enough explored in the literature, neither theoretically nor experimentally. There are some relevant discussions about this type of contributions in two-body B meson decays, which can be extended to three-body decays, where we expect that to be even more important.

In the context of the two-body decay $B \to \pi\pi$, it was argued that the direct B meson decay to a colorless $q\bar{q}$ state, which is produced with a high relative momentum, leads to a small FSI effects in the $\pi\pi$ channel [8]. This was found to be incorrect in [9], where it was shown that the meson-meson S-wave interaction around m_b energies is expected be large, since soft FSI grows with energy. However, perturbative calculations usually miss this feature, since it is a nonperturbative process in nature. The relevance of the soft FSI was also discussed in [10], where the estimated strong phase from the inelastic scattering becomes very relevant if the decay channel has a large probability as a final state. The possibility of large final state phase-shift effects in two-body B decays are presented also in Ref. [11]. Inelastic rescattering contributions discussed in the context of coupled-channel approaches, Regge exchanges and the use of other hadronic models applied to study two- and three-body decays were presented in [12].

Approaches based on effective field theories, as QCD factorization, perturbative QCD and soft-collinear effective theory, explains many features of B meson decays, but many issues are still difficult to understand. The heavy quark limit is supposed to suppress FSI's due to cancellations occurring between many intermediate states [13]. However, this is not always true for physical values of m_b [14] and in fact can be enhanced by intermediate states with high branching fractions [15]. In Ref. [16] several hadronic two-body B decay channels were examined taking into account soft final state interaction effects. A similar formalism is used to study FSI contribution to $B \to KK$ decays in [17]. It was shown that these contributions can enhance considerably color-suppressed neutral modes and affect significantly CPV calculations that takes into account only short-distance physics. Rescattering processes as $B \to D_s\bar{D} \to K\pi$ and $B \to D\bar{D} \to \pi\pi$ were taking into account and showed to be important. This encouraged us to suggest that the contributions from FSI to three-body decays as $B \to D\bar{D}\pi \to \pi\pi\pi$ would be even larger, since there is a range in the phase-space where the aforementioned rescattering is allowed. The hadronic model from this reference can be used to obtain the normalization of the matrix element for the $DD' \to PP'$ reaction. This transition in the three-body context is associated with a distribution depending on the scattering energy, starting from the DD' threshold until the end of the phase-space. Lattice calculations also may be an important hope for future calculations involving $DD' \to PP'$ transitions, as have been done for the P-wave $\pi\pi \to KK$ coupled-channel, besides some other ones [18].

In Ref. [19] the rescattering of two-pseudoscalars in B decays were analysed making use of the $SU(3)$ flavor symmetry approach, where the matrix elements are parametrized and extracted from data by a fitting procedure without reference to specific models. The free parameters extracted from data in this framework includes all the strong interactions effects, even long-distance physics. In the QCD factorization approach, soft FSI is treated as a non-factorizable effect that contributes to the weak decay amplitude and mostly it is argued that is suppressed for two-body decays [13]. This long distance physics is hard to take into account, since it is very complicated to avoid double counting when considering hadronic and quark-level dynamics together. Moreover, the nonperturbative nature of the hadronic inelastic transitions makes its computation very complicated. However, even within QCDF it is well accepted that there are limitations in the method and the complicated scenario of the three-body decays allow us to think in soft FSI's, at least in some regions of the Dalitz plot [20].

The CP asymmetry constrained by CPT invariance is affected by resonances besides the final state interaction (FSI) [6]. Starting from the CPT constraint, we proposed a generalized CP asymmetry formula including resonances and FSI. A simple B decay model was elaborated with the ρ and $f_0(980)$ resonances plus a non resonant background including the $\pi\pi \to KK$ amplitude. There we performed the fit of the CP asymmetry for the charmless $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ decay and the formula presented a fair agreement with the high statistics LHCb data in the mass region below 1.6 GeV. We obtained as an outcome the CP asymmetry in the $B^{\pm} \to \pi^{\pm}K^{+}K^{-}$ decay from the asymmetry in the $B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-}$ channel. Analogously, the CP asymmetry of the $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}$ decay was also described, and from that the asymmetry in the $B^{\pm} \to K^{\pm}K^{+}K^{-}$ channel was derived. The new LHCb release of the 2011/2012 brings CPV two-body distributions in all three-body channels [7], with light charged pseudoscalars, shows all the previous features for two-body invariant masses below 2 GeV, discussed above. Furthermore it shows new sources of CPV in the high KK, $\pi\pi$, $K\pi$ invariant masses around 4 GeV.

In the following, we sketch the formalism to introduce long distance effects through FSI in the calculation of CP asymmetry considering the CPT constraint. This put in perspective the possibility to account for the contribution due to the coupling between channels with two light pseudoscalars and two charmed mesons to CPV in charmless three-body B decays for two-body masses in the phase-space region around 4 GeV.

2. CPT constrained model and scattering matrix parametrization

In the next we follow closely the formalism developed in [5, 6]. The hadronic state $|h\rangle$ and its charge conjugate $\bar{h}$, transforms under the CPT operator as $CPT\,|h\rangle = \chi\langle\bar{h}|$, where χ is a complex phase. Both, weak and strong Hamiltonians, conserve CPT and the hadron weak decay matrix element reads $\langle\lambda_{out}|H_w|h\rangle$, with the state $|\lambda_{out}\rangle$ including the strong interaction effects. Considering that the weak Hamiltonian is hermitian, the completeness of the strong Hamiltonian eigenstates and requiring CPT invariance, we can introduce the S-matrix element as $S_{\bar{\lambda}',\bar{\lambda}} = \langle\bar{\lambda}'_{out}|\bar{\lambda}_{in}\rangle$.

The partonic decay amplitude can be written factorizing the weak phase $\mathscr{A}^{\pm} = A_\lambda + B_\lambda e^{\pm i\gamma}$, where both A_λ and B_λ are complex and CP invariant amplitudes. They are related with the final state channel, caring the final state interactions, by $\mathscr{A}^{-} = \langle\lambda_{out}|H_w|h\rangle$, and $\mathscr{A}^{+} = \langle\bar{\lambda}_{out}|H_w|\bar{h}\rangle$. It is easy to see that, if we keep only leading order terms in the t-matrix, we find

$$\mathscr{A}^{+}_{LO} = A_{0\lambda} + e^{i\gamma}B_{0\lambda} + i\sum_{\lambda'} t_{\lambda',\lambda}\left(A_{0\lambda'} + e^{i\gamma}B_{0\lambda'}\right). \tag{2.1}$$

This decay amplitude can directly symmetrized redefining the decay amplitude as $\mathscr{A}^{+}_{LO} = \tilde{A} + e^{i\gamma}\tilde{B}$, where $\tilde{A} = \tilde{A}(s_{12}, s_{32}) = \tilde{A}(s_{12}) + \tilde{A}(s_{32})$ and the same for $\tilde{B}$. The CP asymmetry is simply computed by $\Delta\Gamma_\lambda = \Gamma(h \to \lambda) - \Gamma(\bar{h} \to \bar{\lambda})$ and at leading order in $t_{\lambda',\lambda}$ reads

$$\Delta\Gamma_\lambda = 4(\sin\gamma)\,\mathrm{Im}[B^{*}_{0\lambda}A_{0\lambda} + i\sum_{\lambda'}(B^{*}_{0\lambda}t_{\lambda',\lambda}A_{0\lambda'} - B^{*}_{0\lambda'}t^{*}_{\lambda',\lambda}A_{0\lambda})], \tag{2.2}$$

where the external sum of λ' represents each intermediate channel that contributes to the rescattering process. The formula of Eq. (2.2) is manifestly CP invariant as demonstrated in [6], leading to the constraint $\Delta\Gamma_\alpha = -\Delta\Gamma_\beta$, in the case that there are two channels, α and β, coupled by FSI.

The important input to the model is the S-matrix element that describes the inelastic meson-meson rescattering. We can propose a parametrization considering the important physical ingredients involved in the process. Let us first discuss the S-matrix modulus, which is described in [21]. The naive picture of a two-meson inelastic collision is the annihilation of the initial hadronic states producing a $q\bar{q}$ pair that recombines producing the final state particles. The intermediate propagation has a damping factor s^{-1} and the meson break into the $q\bar{q}$ pair, which has an imbalance in the relative momentum that goes with $\approx \sqrt{s}$ and brings a factor as s^{-1} related with the threshold behavior. The threshold behavior depends on the relative momentum between the intermediate $q\bar{q}$ pair and its valence wave function in the asymptotic limit, since we are considering energies around the B meson mass. The valence light-cone wave function in S-wave has an asymptotic behavior like $k_{\perp}^{-2}$ in the transverse momentum [22], which we can naively understand as a damping factor of s^{-1}. Putting these factors together, the S-matrix element has a suppression that goes with s^{-3}. Taking into account the threshold position s_{th}, the Lorentz invariant S-matrix element can be written as $\mathcal{N}\sqrt{s-s_{th}}/s^{3.5}$. The normalization $\mathcal{N}$ ensures that the matrix element is smaller than 1, due to the unitarity constraint. Our formula is also in agreement with the parametrizations of the S-wave isospin zero $\pi\pi \to KK$ scattering of [23].

Now we can go further and discuss the phase-shift parametrization. Our scattering matrix, considering only two channels, is a unitary SU(2) matrix with three parameters to be determined, namely the inelasticity η and the PP' and DD' phase shifts. The diagonal matrix element is written as $S_\lambda = \eta e^{2i\delta_\lambda} = (k\cot\delta_\lambda + ik_\lambda)/(k\cot\delta_\lambda - ik_\lambda)$, where $k_\lambda = \sqrt{s - s_{th\lambda}}/2$ and $s_{th\,\lambda}$ is the threshold of the channel λ. We name $S_{DD'}$ and $S_{PP'}$ the matrix elements representing the elastic processes. According to the discussion in the previous section, we believe that to describe the CP asymmetry in the charmless three-body B decay in the mass region above 4 GeV, and according to Eq. (2.2), the essential ingredient, besides the weak phase, is the S-matrix in the s-wave state for the coupled channels of two light-pseudoscalar and two charmed mesons. Our idea to built the S-matrix constrained by unitarity is to introduce a pole in $k\cot\delta$ in the position $s = s_0$, namely $k\cot\delta_{PP'} = -c/(1 - k_{PP'}/k_{0PP'})$ with $k_{0PP'} = \sqrt{s_0 - s_{th\,PP'}}/2$, which lead to a zero in the CP violation projected distribution, combined with a bound/virtual state in the two charmed meson decay channel [6]. The parameter c is the residue of the pole in $k\cot\delta$ and its origin is dynamical, coming from the elastic phase-shift of the two light pseudoscalars. In $S_{DD'}$ we put a virtual or bound state and introduce a zero in the PP' elastic scattering amplitude in the region around 20 GeV^2. In the unitary limit, we can make the scattering length go to infinity $a \to \infty$ and nothing changes in the result. The zero in the S-matrix is inspired in its non-relativistic counterpart, called Ramsauer-Townsend effect, where the scattering amplitude has a minimum or a zero. We expect that with these ingredients the CP asymmetry in charmeless three-body B decays in the phase-space region of two body masses around 4 GeV can be described. This would reinforce the role of the long-range physics in the observed pattern of the CP asymmetry in three-body decays, and, as a consequence, allow to extract precious information about the diagonal and non-diagonal strong S-matrix elements in that mass region.

References

[1] M. Bander, D. Silverman, and A. Soni, *CP noninvariance in the Decays of Heavy Charged Quark Systems, Phys. Rev. Lett.* **43** (1979) 242.

[2] J.-M. Gérard and W.-S. Hou, *CP Nonconservation and CPT: Reassessment of Loop Effects in Charmless B Decays, Phys. Rev. Lett.* **62** (1989) 855; G. W.-S. Hou, *CP and CPT: Reassessment of Penguin Induced CP Violation in Decays, Nucl. Phys. B (Proc. Suppl.)* **16** (1990) 371.

[3] J.-M. Gérard and W.-S. Hou, *CP violation in inclusive and exclusive charmless B decays, Phys. Rev. D* **43** (1991) 2909.

[4] L. Wolfenstein, *Final-state interactions and* CP *violation in weak decays, Phys. Rev. D* **43** (1991) 151.

[5] I. Bediaga, O. Lourenço, T. Frederico. *CP violation and CPT invariance in $B^{\pm}$ decays with final state interactions, Phys. Rev. D* **89** (2014) 094013.

[6] J. H. Alvarenga Nogueira *et al. CP violation: Dalitz interference, CPT and final state interactions, Phys. Rev. D* **92** (2015) 054010.

[7] R. Aaiji *et al.* (LHCb Collaboration), *Measurements of CP violation in the three-body phase space of charmless $B^{\pm}$ decays Phys. Rev. D* **90** (2014) 112004; Additional figures in LHCb-PAPER-2014-044 (https://cds.cern.ch/record/1751517?ln=en)

[8] J. D. Bjorken, *New Developments in High-Energy Physics, Nucl. Phys. B (Proc. Suppl.)* **11** (1989) 325.

[9] J. F. Donoghue *et al.*, *Systematics of Soft Final-State Interactions in B Decays, Phys. Rev. Lett.* **77** (1996) 2178.

[10] M. Suzuki, L. Wolfenstein, *Final state interaction phase in B decays, Phys. Rev. D* **60** (1999) 074019.

[11] A. F. Falk *et al.*, *Final state interactions and new physics in $\vec{B} \to \pi K$ decays, Phys. Rev. D* **57**, 4290 (1998); B. Blok, M. Gronau, and J. L. Rosner, *Annihilation, Rescattering, and CP Asymmetries in B Meson Decays, Phys. Rev. Lett.* **78**, 3999 (1997).

[12] P. Zenczykowski, *Coupled-channel final-state interactions through Reggeon exchange for $D(B) \to \pi\pi, K\bar{K}$, Phys. Lett. B* **460** (1999) 390; A. Furman *et al.*, *Final state interactions in $B^{\pm} \to K^+K^-K^{\pm}$ decays, Phys. Lett. B* **699** (2011) 102.

[13] M. Beneke *et al.*, *QCD Factorization for $B \to \pi\pi$ Decays: Strong Phases and CP Violation in the Heavy Quark Limit, Phys. Rev. Lett.* **83** (1999) 1914; *QCD factorization for exclusive, non-leptonic B meson decays: General arguments and the case of heavy-light final states, Nucl. Phys. B* **591** (2000) 313; *QCD Factorization in $B \to \pi K$, $\pi\pi$ Decays and Extraction of Wolfenstein Parameters, Nucl. Phys. B* **606** (2001) 245.

[14] A. J. Buras *et al.*, *$B \to \pi\pi$, New Physics in $B \to \pi K$, and Implications for Rare K and B Decays, Phys. Rev. Lett.* **92** (2004) 101804.

[15] M. Gronau, D. London, and J. L. Rosner, *Rescattering contributions to rare B-meson decays, Phys. Rev. D* **87** (2013) 036008.

[16] H.-Y. Cheng, C.-K. Chua, and A. Soni, *Final state interactions in hadronic B decays, Phys. Rev. D* **71** (2005) 014030.

[17] C.D. Lu, Y.-L. Shen and W. Wang, Final state interaction in $B \to KK$ decays, Phys. Rev. D 73 034005 (2006)

[18] D. J. Wilson *et al.*, *Coupled $\pi\pi$, $K\bar{K}$ scattering in P-wave and the ρ resonance from lattice QCD, Phys. Rev. D* **92** (2015) 094502; G. Moir *et al.*, Coupled-Channel $D\pi$, $D\eta$ and D_sK^- Scattering from Lattice QCD, arXiv:1607.07093 [hep-lat] (2016).

[19] C. Smith, *Searching for dominant rescattering sources in decays of B to two pseudoscalars, Eur. Phys. J. C* **33** (2004) 523.

[20] S. Kränkl, T. Mannel, J. Virto, *Three-Body Non-Leptonic B Decays and QCD Factorization, Nucl. Phys. B* **899** (2015) 247.

[21] J.H. Alvarenga Nogueira *et al.* , *Suppressed $B \to PV$ CP asymmetry: CPT constraint, Phys. Rev. D* **94** (2016) 054028.

[22] X. Ji, J.-P. Ma, and F. Yuan, *Generalized Counting Rule for Hard Exclusive Processes, Phys. Rev. Lett.* **90** (2003) 241601.

[23] J. R. Peláez and F. J. Ynduráin, *Pion-pion scattering amplitude, Phys. Rev. D* **71** (2005) 074016.