T-odd and CP-odd triple momentum correlations in the exclusive semi-leptonic charm meson decay \( D \to K^*(K\pi)l\bar{v}_l \)

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Abstract. We study T-odd and CP-odd triple momentum correlations in exclusive semi-leptonic charm meson decays \( D \to K^*(K\pi)l\bar{v}_l \). We define asymmetry ratios that measure the true CP-violating effects, and T-odd triple momentum correlation effects from unitarity contributions. Possible new CP-violating contributions are parametrized in terms of an effective four-fermion Hamiltonian where CP-violating effects should come from new non-standard sources. A detailed analysis of the left-right model and the Weinberg Higgs-boson model of CP-violation is carried out.

Indirect and direct CP-violating effects have so far only been observed in the \( K^0 - K^0 \) system from the \( K_L \to \pi \pi \) branching ratio and a CP asymmetry in \( K_L \to \pi \nu \bar{\nu} \) semileptonic decay [1]. These data, however, can be explained by a number of theoretical models. In order to gain a deeper understanding of the origin of CP-violation, it is necessary to investigate possible CP-violation effects in decay modes as well as in other flavour channels. Possible CP-violating effects in the B-meson sector have been at the focus of theoretical attention. In particular this concerned the study of partial rate asymmetries occurring in different exclusive channels [2]. Recently, a new type of CP-violating signal in triple-product correlations were investigated [3-5].

In particular, the T-odd and CP-odd triple momentum correlations in the exclusive semi-leptonic bottom meson decays \( B \to D^* \to D \pi \to l \bar{v}_l \) were studied in detail by us [4]. We found that the asymmetry ratios that measure these T-odd triple momentum correlation effects would have to come from new non-standard model sources as there are no standard model contributions. Their magnitude was estimated to be \( \mathcal{O}(1\%) \) in some extensions of the standard model. We also found that the strong interaction unitarity contributions are small or, in the case of a particular T-odd observable, absent. A similar discussion can obviously be applied to the exclusive semi-leptonic charm meson decays \( D \to K^*(K\pi) + l + \bar{v}_l \), in which the magnitude of the CP-violating effects is expected to be of the same order as in the \( B \to D^* \to D \pi + l + \bar{v}_l \) decays. In the case of CP-violating partial rates the asymmetries in D-meson decays are much smaller than those in B-meson decays. For these reasons it is important and worthwhile to study the T-odd triple momentum correlations in the decay \( D \to K^*(K\pi) + l + \bar{v}_l \). In addition, the mode \( D \to K^*(K\pi) + l + \bar{v}_l \) has a large branching ratio. Also there is now new experimental information on the form factors that occur in this decay.

The analysis of the T-odd and CP-odd triple momentum correlation effects proceeds in analogy to the case \( B \to D^* \to D \pi + l + \bar{v}_l \) treated in [4]. We begin by writing down a very general effective Hamiltonian including CP-violating effects:

\[
H_{\text{eff}} = \frac{G}{\sqrt{2}} V_{cs} \left[ \left( 1 + \gamma_{LL} \right) \bar{q}_s \gamma_{\mu} (1 - \gamma_5) q_c \bar{L}_1 \gamma_{\nu} (1 - \gamma_5) L_2 \\
+ \gamma_{RL} \bar{q}_s \gamma_{\mu} (1 + \gamma_5) q_c \bar{L}_1 \gamma_{\nu} (1 - \gamma_5) L_2 \\
+ \gamma_{LL} \bar{q}_s (1 - \gamma_5) q_c \bar{L}_1 (1 - \gamma_5) L_2 \\
+ \gamma_{RL} \bar{q}_s (1 + \gamma_5) q_c \bar{L}_1 (1 - \gamma_5) L_2 \right],
\]

(1)

where \( G \) is the weak coupling constant and \( V_{cs} \) is the KM matrix element. The \( q_i \) and \( L_i \) are quark and lepton fields, respectively. In writing down the effective Hamiltonian in (1) we have not included right-handed leptonic currents because any interference between the left- and right-handed leptonic section gives terms proportional to the left neutrino mass which we neglect in this analysis.

The complex coupling coefficients \( \gamma_{LL}, \gamma_{RL}, \gamma_{LL} \) and \( \gamma_{RL} \) parametrize any new physics that would arise from vector and scalar boson exchange including CP-violating
contributions. The standard model prediction is obtained from (1) by setting $Z_{iL}$ and $q_{iL}(i=L,R)$ to zero.

With the effective Hamiltonian in (1), we can write down the angular distribution of the semileptonic cascade decay $D \to K^* \to K \pi l_i$

$$d\Gamma(D \to K^*)/(dK \pi l_i)$$

$$d\Gamma(D \to K^*)/(dK \pi l_i) = \frac{3G^2 |V_{ck}|^2 (q^2 - m_2^2) p_B}{128(2\pi)^4 m_2^2 q^2} B(K^* \to K \pi)$$

$$\cdot \left\{ \left( 1 + \cos^2 \theta + \frac{m_2^2}{q^2} \sin^2 \theta \right) \sin^2 \theta \sin^2 \theta^* \right\}$$

$$\cdot \left\{ \left( 1 - \cos^2 \theta + \frac{m_2^2}{q^2} \sin^2 \theta \right) \sin^2 \theta \sin^2 \theta^* \right\}$$

$$\cdot \left\{ \left( 1 - \cos^2 \theta + \frac{m_2^2}{q^2} \sin^2 \theta \right) \sin^2 \theta \sin^2 \theta^* \right\}$$

$$\cdot \left\{ \left( 1 - \cos^2 \theta + \frac{m_2^2}{q^2} \sin^2 \theta \right) \sin^2 \theta \sin^2 \theta^* \right\}$$

$$\cdot \left\{ \left( 1 - \cos^2 \theta + \frac{m_2^2}{q^2} \sin^2 \theta \right) \sin^2 \theta \sin^2 \theta^* \right\}$$

The invariant momentum transfer squared is denoted by $q^2$ and $p$ is the momentum of the $K^*$ in the $D$ rest system. $\theta$ and $\chi$ are the polar and azimuthal angles of the lepton in the $(\overline{v}_i)$ CM system, $\theta^*$ is the angle between the $K$ and the $K^*$ system in the $K^* \pi$ CM system (see Fig. 1). $B(K^* \to K \pi)$ is the $K^* \to K \pi$ branching ratio and $m_l$ is the lepton's mass. The helicity form factors $H_\sigma(\sigma = \lambda, \gamma, 0)$ and $H$ are defined by

$H_\sigma = \bar{\epsilon}^\sigma *(\sigma) \langle K^* \lambda l_i | A_\mu + V_\mu | D \rangle$ (3a)

and

$H = \langle K^* \lambda l_i | S + P | D \rangle$, (3b)

where $V_\mu$, $A_\mu$, $S$ and $P$ are the vector, axial vector, scalar and pseudoscalar currents, respectively. In our case, the currents take the form

$V_\mu = (1 + \gamma \cdot m_{1L} + \gamma \cdot m_{1R}) q \gamma_\mu q \gamma_\nu l_i$, $A_\mu = -(1 + \gamma \cdot m_{1L} + \gamma \cdot m_{1R}) q \gamma_\mu q \gamma_\nu l_i$, $S = (\eta_{1L} + \eta_{1R}) q \gamma_\mu l_i$, $P = (\eta_{1R} - \eta_{1L}) q \gamma_\mu l_i$, (4)

as can be read off from the effective Hamiltonian (1).

$\bar{\epsilon}_i(\sigma)$ is the polarization vector associated with the currents. $\sigma = \lambda = \pm, 0$ denote the transverse and longitudinal spin 1 components and $\sigma = \lambda = 0$ denotes the time-(or scalar) component of the current transition.

In the angular decay distribution (2), we have separately written out the $T$-even parts in (2a) and the $T$-odd parts in (2b). The $T$-odd nature of contributions (2b) can be exhibited by rewriting them in terms of the triple momentum products which are odd under $T$ as discussed in [4].

We now turn to the discussion of triple momentum correlation measures by defining suitable asymmetry ratios as in [4]. To this end we partition the full physical angular ranges into the following sub-domains:

$(\chi)$

I: $0 \leq \chi < \pi/2$, 
II: $\pi/2 \leq \chi < \pi$, 
III: $\pi \leq \chi < 3\pi/2$, 
IV: $3\pi/2 \leq \chi < 2\pi$.

$(\theta)$

A: $0 \leq \theta < \pi/2$, 
B: $\pi/2 \leq \theta < \pi$.

The last line of (2b) contains the contribution of a possible scalar exchange that would be generated by the last two lines of the effective Hamiltonian (1). Equation (2) holds for the decays $D(c) \to K^*(s) l^- \overline{v}_i$. For the corresponding decays $\bar{D}(c) \to K^*(s) l^- \overline{v}_i$ one needs to change the signs of the parity violating terms.