BARYON POLARIZATION,
PHASES OF AMPLITUDES
AND TIME REVERSAL ODD OBSERVABLES

E. DI SALVO
Laboratoire de Physique Corpusculaire de Clermont-Ferrand,
IN2P3/CNRS Université Blaise Pascal, F-63177 Aubière Cedex, France
disalvo@ge.infn.it

Z.J. AJALTOUNI
Laboratoire de Physique Corpusculaire de Clermont-Ferrand,
IN2P3/CNRS Université Blaise Pascal, F-63177 Aubière Cedex, France

We elaborate two different methods for extracting from data the relative phase of two amplitudes of some sequential decays of baryons. We also relate this phase to a particular physical angle. Moreover, we suggest how to infer some time reversal odd observables - in particular, asymmetries - from data. Lastly, we comment on the standard model predictions of such asymmetries, showing that most of the decays considered are quite suitable for revealing possible new-physics contributions.

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1. Introduction

The search for new physics (NP) beyond the standard model (SM) is the main goal of present high energy physics. To this end, several facilities have been realized or planned. At the same time, different methods have been elaborated, in order to find hints to NP. In particular, as regards hadron decays, people try to single out and measure observables which are sensitive as much as possible to deviations from the SM. We mention among them the T-odd correlations \[^{12}\] and asymmetries \[^{13},^{14}\] associated to kinematic variables which change sign at inverting all momenta and angular momenta involved \[^{15}\]. These may be extracted, for example, from sequential weak two-body decays involving more spinning particles in the primary decay \[^{16}\]. This kind of observable, wherever usable, looks more convenient than direct CP asymmetry, in that it does not depend so dramatically on the
relative strong phase-shift of the interfering amplitudes. It has been employed in some experiments. Also T-even asymmetries may be quite helpful, although almost neglected in the literature.

We have studied in a previous paper single and double asymmetries connected to weak sequential decays, in order to infer suitable T-even and T-odd observables, sensitive to hints to NP. Here we focus on a particular kind of such decays, consisting of two successive weak processes of the type

\[ J \rightarrow a \ b, \quad a \rightarrow a_1 \ a_2. \]  

Here \( J, a \) and \( a_1 \) are spin-1/2 baryons, \( b \) is a spin-0 or spin-1 meson and \( a_2 \) a spin-0 meson. We recall a previous result on these decays, giving it a simple geometrical interpretation. Moreover we elaborate two different methods for extracting from data the relative phase of two decay amplitudes; to this end, we define a T-even and a T-odd single asymmetry. The convenience of each method depends on the available statistics. We note that a nonzero T-odd asymmetry does not necessarily imply time reversal (TR) violation; however, if also data of the CP-conjugated decay may be analyzed, our methods allow to determine some observables which are odd under TR. Obviously, comparing the experimental results of these observables with their SM predictions, can in principle help detecting possible discrepancies, and therefore signatures of NP.

Here we list some decays of the type mentioned above, of current interest, to which our methods may be applied:

\[ \Lambda_b \rightarrow \Lambda(\Lambda^+), \quad P(V), \quad \Lambda^+_c \rightarrow \Lambda \ \pi^+, \quad \Xi \rightarrow \Lambda \ \pi. \]  

Here \( P(V) \) denotes a light, pseudoscalar (vector) meson. We need also correlation with the secondary decay of the fermion, that is, e.g.,

\[ \Lambda \rightarrow p \ \pi^-, \]  

or the second decay \[ \text{[2]}, \] if \( \Lambda^+_c \) is observed in the primary decay. Data of such decays are available mainly from Fermilab experiments; in particular, \( \Lambda_b \) and \( \Lambda_c \) decays have been investigated recently at CDF \[ \text{[14,15]} \] and D0 \[ \text{[16,17]} \]. For the hyperon decay we signal refs. \[ \text{[18,19,20]} \]. The \( \Lambda_b \) and \( \Lambda_c \) decays have raised also a lively theoretical interest \[ \text{[21,22,23,24]} \], as well as \[ \text{[25]} \], which may be detected at the new facilities, like LHCb.

The present note is organized as follows. In sect. 2 we introduce suitable reference frames for describing the sequential decay. Then we define operatively T-even and T-odd asymmetries, giving their analytical expressions in terms of physically interesting observables. Lastly, we expose several remarks, illustrating a geometrical interpretation of our results, and we describe our first method for determining a T-even and a T-odd observable. In sect. 3 we suggest an alternative method, suitable in presence of a relatively scarce statistics. In sect. 4 we show how to determine
real TR-odd observables, provided data of the CP-conjugated decay are available.
Finally, sect. 5 is devoted to comments on the SM predictions of the asymmetries
connected to the above mentioned decays, with a comparison with NP contributions,
and to a short conclusion.

2. T-odd and T-even Asymmetries
Here we introduce some T-odd and T-even asymmetries, which can be inferred from
sequential decays of the type \( (1) \). They are defined as

\[
A = \frac{N(p > 0) - N(p < 0)}{N(p > 0) + N(p < 0)},
\]

where \( p \) is a given T-odd or T-even variable and \( N(p > 0) \) [\( N(p < 0) \)] the number
of decays such that \( p \) is positive (negative).

Our variables are conveniently defined in suitable reference frames, that we are
going to define.

2.1. Reference Frames
First of all, we recall the definition of a canonical frame, at rest with respect to the
parent resonance \( J \):

\[
\hat{y} = \frac{p_{in}}{|p_{in}|}, \quad \hat{z} = \frac{p_{in} \times p_J}{|p_{in} \times p_J|}, \quad \hat{x} = \hat{y} \times \hat{z},
\]

where \( p_{in} \) and \( p_J \) are, respectively, the momenta of the initial beam and of the
resonance \( J \) in the laboratory frame.

On the other hand, the secondary decay, \( i.e. \) of particle \( a \), is more conveniently
described in the helicity frame. To this end we define the following three mutually
orthogonal unit vectors:

\[
\hat{e}_L = \frac{p_a}{|p_a|}, \quad \hat{e}_T = \frac{\hat{z} \times \hat{e}_L}{|\hat{z} \times \hat{e}_L|}, \quad \hat{e}_N = \hat{e}_T \times \hat{e}_L,
\]

\( p_a \) being the momentum of \( a \) in the canonical frame.

2.2. Asymmetries
We define the T-odd and the T-even variable respectively as

\[
p_N = p_{a_1} \cdot \hat{e}_N, \quad p_T = p_{a_1} \cdot \hat{e}_T,
\]

that is, the normal and transverse component of the momentum \( p_{a_1} \) of particle \( a_1 \)
in the rest frame of \( a \). We denote the corresponding asymmetries, defined by Eq.
as $A_N$ and $A_T$. Their expressions read

\[ \Gamma(\Omega)A_N(\Omega) = \frac{1}{2\pi} W \Delta a^s [\Re(\alpha_{1/2,0}^{\ast} \alpha_{-1/2,0}) P_N + \Im(\alpha_{1/2,0}^{\ast} \alpha_{-1/2,0}) P_T], \]  

\[ \Gamma(\Omega)A_T(\Omega) = \frac{1}{2\pi} W \Delta a^s [\Im(\alpha_{1/2,0}^{\ast} \alpha_{-1/2,0}) P_N - \Re(\alpha_{1/2,0}^{\ast} \alpha_{-1/2,0}) P_T]. \]

Here $\Gamma(\Omega)$ is the differential decay width, $\Omega$ denoting the direction of the momentum of particle $a$ in the canonical frame: as usual, we have set $\Omega \equiv (\theta, \phi)$, where $\theta$ and $\phi$ are, respectively, the polar and azimuthal angle. Moreover

\[ W = |B(p_a^2)|^2 |B(p_b^2)|^2 |B(p_0^2)|^2 \]

and the $B(p^2)$’s are the relativistic Breit-Wigner functions of the resonances, normalized as

\[ \int_0^\infty dp^2 |B(p^2)|^2 = 1. \]

The $a_{\lambda_a, \lambda_b}$’s are defined as

\[ a_{\lambda_a, \lambda_b} = \frac{T_{\lambda_a, \lambda_b}}{\sqrt{\sum_{\lambda_a, \lambda_b} |T_{\lambda_a, \lambda_b}|^2}}, \]

the $T_{\lambda_a, \lambda_b}$’s being the helicity decay amplitudes of the parent resonance and $\lambda_a(\lambda_b)$ the helicity of particle $a(b)$. Similarly, we have set

\[ \Delta a^s = \frac{1}{2}(a^s_+ - a^s_-) \quad \text{and} \quad a^s_\pm = \frac{|A^s_\pm|^2}{|A^s_+|^2 + |A^s_-|^2}, \]

where the $A^s_\pm$’s are the two helicity decay amplitudes of the baryon $a$. Furthermore,

\[ \Gamma(\Omega) = \frac{1}{4\pi} W (1 + P_L \Delta G_L), \]

where $\Delta G_L$ is defined as

\[ \Delta G_L = |\alpha_{1/2,0}|^2 - |\alpha_{-1/2,0}|^2 - |\alpha_{1/2,1}|^2 + |\alpha_{-1/2,-1}|^2, \]

with $\alpha_{1/2,1} = \alpha_{-1/2,-1} = 0$ if the meson $b$ has spin 0. Lastly

\[ P_L = \vec{P} \cdot \hat{e}_L, \quad P_N = \vec{P} \cdot \hat{e}_N, \quad P_T = \vec{P} \cdot \hat{e}_T \]

are the components according to the helicity frame of the polarization vector $\vec{P}$ of $J$. These depend on the angles $\theta$ and $\phi$, as we have

\[ \hat{e}_L \equiv (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta), \]
\[ \hat{e}_T \equiv (-\sin\phi, \cos\phi, 0), \]
\[ \hat{e}_N \equiv (-\cos\theta\cos\phi, -\cos\theta\sin\phi, \sin\theta). \]

\[^{a}\text{Eqs. (9) and (10) differ from those in ref. [9] by a factor of 2 at the denominator. This is due to a different definition of the polarization, coherent with Eqs. (27) below.}\]
2.3. Remarks

A) Setting

\[ F = \alpha_{1/2,0} \alpha_{-1/2,0}^* \]  

(21)

Eqs. (9) and (10) imply that the quantities \( \Re F \) and \( \Im F \) are, respectively, T-even and T-odd, since according to our definitions \( A_T \) and \( P_T \) are T-even, while \( A_N \) and \( P_N \) are T-odd. As explained in the introduction, a nonzero value of \( \Im F \) would not necessarily imply TR violation (TRV), since it may be produced also by strong or electromagnetic final-state interactions (FSI), for example by spin-orbit interaction \(^{26,27}\), in the final state. Electromagnetic FSI are small and calculable \(^{28}\). On the contrary, strong FSI are sizable and difficult to calculate. We shall see below that, under some specific conditions and quite general assumptions, they may be disentangled experimentally from the effects of real TR.

B) Eqs. (9) and (10) can be rewritten as

\[ A'_{\perp i}(\Omega) = CR(\Phi) P_{\perp j}(\Omega). \]  

(22)

Here we have introduced the two-dimensional vectors

\[ \vec{P}_{\perp} \equiv (P_N, P_T) \quad \text{and} \quad \vec{A}'_{\perp} \equiv (A'_N, A'_T) \]  

(23)

in a plane perpendicular to \( p_a \), with

\[ A'_N = A'_N(\Omega) = \Gamma(\Omega) A_N(\Omega), \quad A'_T = A'_T(\Omega) = -\Gamma(\Omega) A_T(\Omega). \]  

(24)

Moreover

\[ \Phi = \arg(F) \]  

(25)

and \( R(-\Phi) \) is a rotation matrix such that the vector \( \vec{P}_{\perp} \) goes over into the direction of \( \vec{A}'_{\perp} \); it is defined by \( R_{NN} = R_{TT} = \cos \Phi, \ R_{TN} = -R_{NT} = \sin \Phi \). Lastly, \( C \) is a constant,

\[ C = \frac{1}{2\pi} W \Delta a^* |F|. \]  

(26)

Therefore we conclude that the vectors (23) are connected to each other by a rotation by an angle opposite to the relative phase of the amplitude \( A_{1/2,0}^J \) to \( A_{-1/2,0}^J \).

C) These two-dimensional vectors are observable quantities, which can be inferred from experiment. In particular, thanks to Eqs. (17) to (20), \( P_N \) and \( P_T \) are related to the components \( P_x, P_y, P_z \) of \( \vec{P} \) with respect to the canonical frame. These components can be deduced from the density matrix of the parent resonance \( J \),

\[ \rho_{\pm\pm} = \frac{1}{2}(1 \pm P_z), \quad \rho_{\pm\mp} = \frac{1}{2}(P_x \pm i P_y), \]  

(27)

which in turn can be determined from the differential width of the sequential decay. Therefore the modulus \( |F| \) and the phase \( \Phi \) - or equivalently \( \Re F \) and \( \Im F \) - can be
deduced from Eqs. [9] - [10] or [22]. \( \Phi \) can be determined independently of the constant \( C \):

\[
\tan(\Phi) = \frac{\vec{\mathbf{A}}' \times \vec{\mathbf{P}}_\perp \cdot \hat{\mathbf{e}}_L}{\vec{\mathbf{A}}' \cdot \vec{\mathbf{P}}_\perp}.
\]

The ambiguity of \( \Phi \) up to \( \pi \), which derives from Eq. [28], can be resolved by introducing the solution into Eqs. [22].

D) One can show that the asymmetries \( A'_N \) and \( A'_T \) do not coincide with the components of the polarization of the baryon \( a \), when emitted in a given direction \( \Omega \). However, the normal and transverse components of the polarization of the baryon \( a \), averaged over the whole solid angle, read

\[
\mathcal{P}_N^a = \frac{\pi}{2} \mathcal{P}_z \Re F, \quad \mathcal{P}_T^a = -\frac{\pi}{2} \mathcal{P}_z \Im F,
\]

as is straightforward to check. Note that \( \mathcal{P}_N^a(T) \) is T-odd (T-even), since \( \mathcal{P}_z = \vec{\mathbf{P}} \cdot \hat{\mathbf{z}} \) is T-odd according to the second Eq. [6]. Result [29] can be obtained also in a different way. Indeed, let us integrate the differential width [9] of the sequential decay [1] over the solid angle \( \Omega \) and over the polar angle of the momentum of \( a_1 \) in the helicity frame. We get

\[
\Gamma(\phi_1) = \frac{1}{2\pi} W[1 + \frac{\pi^2}{2} \Delta a_s^a \mathcal{P}_z \Re(F e^{i\phi_1})].
\]

Here \( \phi_1 \) is the azimuthal angle of the momentum of \( a_1 \) in the helicity frame. Comparing Eq. [30] with the general formula

\[
\Gamma(\phi_1) = \frac{1}{2\pi} W[1 + \frac{\pi}{2} \Delta a_s^a \Re(\rho_+ e^{i\phi_1})],
\]

and taking account of Eqs. [27], leads again to formulae [28]. Note that, if the expression [30] is used for fitting data, one can infer the values of \( \mathcal{P}_N^a \) and \( \mathcal{P}_T^a \), and therefore \( F \).

Moreover Eqs. [28] imply
- that \( \Phi \) can be determined independently of \( \mathcal{P}_z \):

\[
\tan(\Phi) = -\frac{\mathcal{P}_T^a}{\mathcal{P}_N^a};
\]

- that Eqs. [9]-[10] or [22] can be rewritten as

\[
\Gamma(\Omega) A_N(\Omega) = C' \vec{\mathbf{P}}_\perp \cdot \vec{\mathbf{P}}'_\perp, \quad \Gamma(\Omega) A_T(\Omega) = C' \vec{\mathbf{P}}_\perp \times \vec{\mathbf{P}}'_\perp \cdot \hat{\mathbf{e}}_L,
\]

where \( \vec{\mathbf{P}}'_\perp = (\mathcal{P}_N^a, \mathcal{P}_T^a) \) and \( C' = 2C'/(\pi \mathcal{P}_z) \).

E) Lastly, one has to observe that, in the production process of the parent resonance \( J \), strong interactions contribute only to the \( z \)-component of the polarization \( \vec{\mathbf{P}} \), due to parity conservation. At sufficiently high energies, also weak interactions contribute, giving rise to nonzero values of the other components.
3. An Alternative Method

Now we propose an alternative method, recommended when the available data is relatively poor. To this end, we define some integral quantities:

\[ B_N(T) = \int d\Omega A_N(T)(\Omega), \quad (34) \]
\[ \Delta B^x_N(T) = \int_0^\pi \sin \theta d\theta \left[ \int_0^\pi - \int_{2\pi}^\pi \right] A_N(T)(\Omega), \quad (35) \]
\[ \Delta B^y_N(T) = \int_0^\pi \sin \theta d\theta \left[ \int_{\pi/2}^{\pi/2} - \int_{3/2\pi}^{\pi/2} \right] A_N(T)(\Omega). \quad (36) \]

Experimentally, these observables amount to

\[ B_N(T) = \pm \frac{N(p_N(T) > 0) - N(p_N(T) < 0)}{N_{tot}}, \quad (37) \]
\[ \Delta B^x_N(T) = \pm \frac{N(p_N(T) \cdot p_x^a > 0) - N(p_N(T) \cdot p_x^a < 0)}{N_{tot}}, \quad (38) \]
\[ \Delta B^y_N(T) = \pm \frac{N(p_N(T) \cdot p_y^a > 0) - N(p_N(T) \cdot p_y^a < 0)}{N_{tot}}. \quad (39) \]

Here \( N_{tot} \) is the total number of events and the \(+(-)\) sign refers to the index \( N(T) \) of the above quantities. Moreover \( p_x^a \) is the \( x \)-component of \( p_a \) with respect to the canonical frame. Inserting Eqs. (22) into (34)-(36) yields

\[ B_N = \pi^2 CR_{NN}(-\Phi)P_z, \quad B_T = \pi^2 CR_{TN}(-\Phi)P_z, \quad (40) \]
\[ \Delta B^x_N = -8CR_{NT}(-\Phi)P_x, \quad \Delta B^y_N = +8CR_{NT}(-\Phi)P_y, \quad (41) \]
\[ \Delta B^x_T = -8CR_{TT}(-\Phi)P_x, \quad \Delta B^y_T = +8CR_{TT}(-\Phi)P_y. \quad (42) \]

We can determine the phase \( \Phi \) and the modulus \( |F| \) from Eqs. (40)-(42), since the polarization of \( J \) and the moments (37)-(39) are experimental quantities. In particular, the ratio

\[ r = \frac{B_T}{B_N} = \tan(\Phi) \quad (43) \]

allows to determine \( \Phi \) independently of \( P_z \), the ambiguity of the phase being resolved by the signs of \( B_N \) and \( B_T \). Analogous ratios can be defined from Eqs. (40) and (41). Therefore we can infer the relative phase of the amplitude \( A_{1/2,0}^J \) to \( A_{-1/2,0}^J \) by just determining the moments (37)-(39).

4. Inferring Time Reversal Odd Observables

As seen above, \( \Re F \) is T-even, while \( \Im F \) is T-odd. But

\[ \Re F = |F| \cos \Phi, \quad \Im F = |F| \sin \Phi. \quad (44) \]

Therefore \( \Phi \) itself must be T-odd. We set, without loss of generality,

\[ \Phi = \Phi_c + \Phi_o. \quad (45) \]
where $\Phi_{e(o)}$ is even (odd) under TR. Therefore, while $\Phi_o$ is sensitive to real TRV, $\Phi_e$ is a consequence of the fake T-odd effects caused by, say, spin-orbit interactions. Now we consider the decay which is CP-conjugated to (11) and define

$$\bar{F} = \bar{\alpha}_{-1/2,0} \bar{\alpha}^*_{1/2,0} = |\bar{F}| e^{i\bar{\Phi}},$$

where the barred symbols denote the quantities relative to this decay. In particular, the phase

$$\bar{\Phi} = \bar{\Phi}_e + \bar{\Phi}_o,$$

may be determined by a procedure analogous to the one suggested for the phase $\Phi$. But, if we assume the CPT symmetry, TR-even (TR-odd) terms are also CP-even (CP-odd). Then

$$\bar{\Phi}_e = \Phi_e, \quad \bar{\Phi}_o = -\Phi_o.$$

The phases $\Phi_e$ and $\Phi_o$ are observables, as they can be deduced from Eqs. (45), (47) and (48). In this connection, it is useful to define the TR-odd asymmetry

$$A_\Phi = \frac{\Phi - \bar{\Phi}}{\Phi + \bar{\Phi}} = \frac{\Phi_o}{\Phi_e}.$$  

Note that, while $\Phi_o$ is TR-odd, $\Phi_e$ is a fake T-odd observable. Three more TR-odd asymmetries can be defined, i.e.,

$$A_F = \frac{|F| - |\bar{F}|}{|F| + |\bar{F}|}, \quad A_R = \frac{\Re(F - \bar{F})}{\Re(F + \bar{F})}, \quad A_I = \frac{\Im(F - \bar{F})}{\Im(F + \bar{F})}.$$  

Lastly we point out that the denominator of $A_I$, that is

$$I_e = \Im(F + \bar{F}),$$

is another fake T-odd observable. Of course, this kind of observables is as useful as real TR-odd ones in the search for NP.

5. Comments on SM and NP Predictions of the TRV Asymmetries

We devote this last section to comments on predictions of the TRV asymmetries defined above, for the decays (2) and (4), both in the framework of the SM and according to NP contributions.

First of all, we observe that the two asymmetries $A_N$ and $A_T$ are sensitive, not only to the relative phase $\Phi$ of the two reduced amplitudes $\alpha_{1/2,0}$ and $\alpha_{-1/2,0}$, but also to the normal and transverse component of the polarization of the parent baryon, $P_N$ and $P_T$. As observed by other authors, this is an advantage over the $B$-decays to two vector mesons, which are insensitive to the spin of the $b$-quark, and whose triple product asymmetries undergo a strong suppression. Therefore, we can reasonably assume that the T-odd asymmetries defined in the present note are of the order of those calculated for the quarks involved in analogous decays.
Now let us examine in more detail the various decays considered in the introduction. Nonzero asymmetries are expected in $\Lambda_b \to \Lambda(\pi^+\pi^-)\rho^0 - \omega$, where the two vector mesons interfere, and in $\Xi^0 \to \Lambda\pi^0$. Both decays derive contributions from the penguin diagram and from the color-suppressed tree diagram, which are kinematically different and have different weak phases, and therefore are suitable for producing nonzero TRV asymmetries of the type (49) and (50). In particular, the tree diagram in the decay $\Lambda_b \to \Lambda(\pi^+\pi^-)\rho^0 - \omega$ is strongly Cabibbo suppressed; moreover the SM predictions of the TRV asymmetries related to this decay are of order 6 percent, while they are increased up to about 50 percent by NP contributions. On the contrary, the decay of $\Xi^0 \to \Lambda\pi^0$ is characterized by a much more consistent contribution of the color-suppressed tree, only slightly Cabibbo suppressed; therefore it may give rise to sizable TRV asymmetries.

The other decays considered in the present note give rise to negligibly small TRV asymmetries according to the SM. This is especially the case of those decays which involve a $b \to c$ or a $c \to s$ transition: indeed, they are driven essentially by a color-allowed and a color-suppressed tree diagram, which are kinematically different, but have approximately the same weak phase. However, if we consider NP possible contributions to such decays, the predictions of the asymmetries are of order 10 to 20 percent.

To conclude, we have shown that some baryon sequential two-body decays can be exploited for extracting the relative phase $\Phi$ and the product of the moduli $F$ of the reduced decay amplitudes $\alpha_{1/2,0}^{1/2,0}$ and $\alpha_{-1/2,0}$ of the parent baryon $J$. To this end, we have defined two asymmetries, which we regard as the components of the two-dimensional vector $\vec{A}'_\perp$, lying in a plane orthogonal to the momentum of the intermediate baryon $a$. $\vec{A}'_\perp$ is related to the projection of the polarization vector of $J$ onto the same plane, by a rotation, whose angle is $-\Phi$. In order to determine $\Phi$ and $F$, two different methods are elaborated. If also data of the CP-conjugated decay may be analyzed, some important observables and TRV asymmetries can be inferred. They are especially sensitive to NP contributions in most of the decays considered, and therefore quite useful for singling out possible deviations from the SM.

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