CP Symmetry and Time Reversal in $\Lambda_b \to \Lambda V(1^-)$

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"Λ_b Decays into Λ-Vector", Physics Letters B614 (2005), 165-173;
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I)- Physical Motivations : $\Lambda_b \to \Lambda V(1^-)$

II)- Kinematics of Cascade Decays.

III)- Dynamics Model for Λ_b Decays.

IV)- Physical Results :
$\star$ Branching Ratios,
$\star$ Asymmetries,
$\star$ Polarizations,
$\star$ Time-Odd Observables.

V)- Perspectives.

I- Physical Motivations

$\approx 10\%$ of produced $b\bar{b}$ pairs hadronize into Beauty Baryons :
$\mathcal{B}_b = \Lambda_b,\ \Sigma_b,\ \Xi_b, \ldots$
$\approx 90\%$ of $\mathcal{B}_b$ dominated by $\Lambda_b(\bar{\Lambda}_b)$.

$$\Downarrow$$

- Testing the validity of **CP** symmetry in Beauty Baryons like in ordinary Hyperons :

$$\Gamma(\mathcal{B}_b \to X) \neq \Gamma(\bar{\mathcal{B}}_b \to \bar{X}) \oplus \text{ Other Observables}$$

- Further Step :

$$\text{Hyperon } \mathcal{B}_s \longleftrightarrow \ Baryon\ \ \mathcal{B}_b$$

$$\Downarrow$$

s-quark replaced by b-quark

$$\Downarrow$$

Significant Increase of the number of tests of both CP and TR Symmetries.

Main Properties of TR Operator

$$\vec{r} \to \vec{r},\ \vec{p} \to -\vec{p},\ \vec{\ell} = \vec{r} \times \vec{p} \to -\vec{\ell},\ \text{spin } \vec{s} \to -\vec{s}$$

AND

Initial State $\longleftrightarrow$ Final State

BUT

Impossibility to realize in Nature the Time-Reversed process of a physical one, like β decay, $\Lambda \to p\pi^-$

SO

$*$ Initial and Final States are NOT interchanged

$\Downarrow$

Time-Odd Operator $\neq$ Time-Reversal

$\Downarrow$

$\star$ Pseudo-Scalar Observables which change sign under TR :

Triple Product Correlations (TPC)

$$\vec{v_i} = \vec{p_i}, \vec{s_i} \ , \ C_{ijk} = \vec{v_i} \cdot (\vec{v_j} \times \vec{v_k}) \longrightarrow TR \to -C_{ijk}$$

like Transverse Polarization : $\vec{s_i} \cdot (\vec{p_j} \times \vec{p_k})$

IF : $< C_{ijk} > \neq 0$ $\equiv$ distribution of C_{ijk} is not symmetric

$\Downarrow$

Sign of T-Odd effect

- T-Odd effect can be taken as a "Serious Candidate" for a TRV process if :

$*$ FSI are negligible.

OR

$*$ FSI can be computed and subtracted from the data.

- Standard Channels whith negligible FSI :

(London et al, Aliev et al, Chen et al).

$\Downarrow$

$$\Lambda_b \to Baryon\ (Hyperon)\ell^+\ell^-, \quad Baryon\ (Hyperon)h^+h^-$$

$*$ 3 Body Final States; $\ell^\pm$ or $h^\pm$ not originating from an Intermediate Resonance.

Another Approach

(Z.J.Ajaltouni, E.Conte, O.Leitner)

$\ast$ Emphasis on Physical Observables constructed from 2 Intermediate Resonances :

$$\Lambda_b \to \Lambda V(1^-), \quad \Lambda \to p\pi^-, \quad J/\psi \to \mu^+\mu^-, \quad \rho^0(\omega) \to \pi^+\pi^-$$

Physical Properties of these Channels

Weak Decay of the $\Lambda_b \Longrightarrow$ Two Polarized Intermediate Resonances.

$\Downarrow$

(1) Component(s) of the Vector-Polarization $\vec{\mathcal{P}}$ NOT invariant by TR

(2) Constructing many TPC, C_{ijk}

$\Downarrow \ \Downarrow \ \Downarrow$

New Insights in the Decay Dynamics.

II- Kinematics of Cascade Decays

- Λ_b is Transversally Polarized because of a QCD mechanism at the partonic level.

- Laboratory Frame :

$\vec{p_1} =$ Incident Proton momentum , $\vec{p_b} = \Lambda_b$ momentum

$$\Downarrow \quad \Downarrow$$

$$\vec{e_1} = \vec{p_1}/p_1 \ , \ \vec{e_3} = \frac{\vec{p_1} \times \vec{p_b}}{|\vec{p_1} \times \vec{p_b}|} \ , \ \vec{e_2} = \vec{e_3} \times \vec{e_1}$$

with

$$\mathcal{P}^{\Lambda_b} \ = < \vec{S_{\Lambda_b}} \cdot \vec{e_3} > = \ \rho_{++}^{\Lambda_b} - \rho_{--}^{\Lambda_b} \neq 0$$

- Final Spin configurations in the Λ_b Transversity frame :

$$\Lambda_b(M_i) \Longrightarrow \Lambda(\lambda_1)V(\lambda_2)$$

$$(\lambda_1, \lambda_2) = (1/2, 0) \ , \ (1/2, 1) \ , \ (-1/2, -1) \ , \ (-1/2, 0)$$

$$M_i = \pm 1/2 \quad , \quad M_f = \lambda_1 - \lambda_2 \ = \ \pm 1/2.$$

Decay Amplitude expressed in the Jacob-Wick-Jackson (JWJ) formalism

- 1^{st} step : Λ_b Decay

$$A_0(M_i) = \langle 1/2, M_i | S^{(0)} | p, \theta, \phi; \lambda_1, \lambda_2 \rangle = \mathcal{M}_{\Lambda_b}(\lambda_1, \lambda_2) D^{1/2\star}_{M_i M_f}(\phi, \theta, 0) \tag{1}$$

$$D^j_{M_i M_f}(\phi, \theta, 0) = d^j_{M_i M_f}(\theta) \exp\left(-i M_i \phi\right)$$

- 2^{nd} step : Resonance Decays in their Helicity Frame
  $A_1(\lambda_1)$ and $A_2(\lambda_2)$

- 3^{rd} step : Total Decay Amplitude

$$\mathcal{A}_I = \sum_{\lambda_1, \lambda_2} A_0(M_i) A_1(\lambda_1) A_2(\lambda_2) \ . \tag{2}$$

$\Longrightarrow$ Decay Probability, $d\sigma$, with Λ_b PDM

$$d\sigma \propto \sum_{M_i, M_i'} \rho^{\Lambda_b}_{M_i M_i'} \mathcal{A}_I \mathcal{A}_I^* \tag{3}$$

• BUT , Parity Violation in Weak Hadronic Decays :

$$\Downarrow \ \Downarrow$$

Helicity Asymmetry parameter, $\alpha_{AS}^{\Lambda_b}$

$$|\Lambda_b(+)|^2 = |\mathcal{A}_{(1/2,0)}(\Lambda_b \to \Lambda V)|^2 + |\mathcal{A}_{(-1/2,-1)}(\Lambda_b \to \Lambda V)|^2 \ , \tag{4}$$

$$|\Lambda_b(-)|^2 = |\mathcal{A}_{(-1/2,0)}(\Lambda_b \to \Lambda V)|^2 + |\mathcal{A}_{(1/2,1)}(\Lambda_b \to \Lambda V)|^2 \ , \tag{5}$$

$$\alpha_{AS}^{\Lambda_b} = \frac{|\Lambda_b(+)|^2 - |\Lambda_b(-)|^2}{|\Lambda_b(+)|^2 + |\Lambda_b(-)|^2} \ , \tag{6}$$

$$\Downarrow\Downarrow$$

Differential Cross-Section :

$$\frac{d\sigma}{d\Omega} \propto 1 + \alpha_{AS}^{\Lambda_b} \mathcal{P}^{\Lambda_b} \cos\theta + 2\alpha_{AS}^{\Lambda_b} \Re e(\rho_{+-}^{\Lambda_b} \exp i\phi) \sin\theta \ . \tag{7}$$

We notice :

⋆ Importance of the Polarization Density Matrix of the produced Λ_b.

III- Dynamics Model for Λ_b Decays

$\star$ New insights in the estimation of the Hadronic Matrix Elements (O.Leitner).

$\star$ Factorization Procedure

$$\text{H.M.E.} = \text{Current Products} \otimes \text{Form Factors.}$$

Form Factors

$\star$ Computed in the framework of Heavy Quark Effective Theory, HQET.
$\star$ Corrections of order $\mathcal{O}(1/m_b)$ are performed.

$$\Downarrow$$

Estimation of the Λ_b wave-function.

Effective Field Theory (OPE)

$\star$ OPE formalism used to evaluate both the soft contributions and the hard ones.

$\Longrightarrow$

$$\mathcal{H}^{eff} = \frac{G_F}{\sqrt{2}} V_{qb} V_{qs}^{\star} \sum_{i=1}^{2} c_i(m_b) O_i(m_b) \ , \tag{8}$$

$*$ $c_i(m_b) =$ Wilson Coefficients representing the Perturbative (hard) part.
$*$ $O_i(m_b) =$ Operators representing the Non-Perturbative (soft) part.

$\star$ Both Tree and Penguin Diagrams are computed.

$$\mathcal{A}_{(\lambda_1,\lambda_2)}(\Lambda_b \to \Lambda V) = \frac{G_F}{\sqrt{2}} f_V E_V \langle \Lambda | \bar{s}\gamma_\mu(1-\gamma_5) b | \Lambda_b \rangle_{(\lambda_\Lambda, \lambda_V)} \tag{9}$$

$$\left\{ \mathcal{M}^T_{\Lambda_b}(\Lambda_b \to \Lambda V) - \mathcal{M}^P_{\Lambda_b}(\Lambda_b \to \Lambda V) \right\} \ , \tag{10}$$

with

$$\mathcal{M}^{T,P}_{\Lambda_b}(\Lambda_b \to \Lambda V) = V^{T,P}_{ckm} A^{T,P}_V(a_i) \ . \tag{11}$$

$a_i =$ Combinations of W.C. according to the nature of $V(1^-)$.

Current Matrix Element

⋆ Four amplitudes related respectively to the 4 Helicity Final States :

$$
\mathcal{M}_{\Lambda_b}(\Lambda_b \to \Lambda V) = \begin{cases}
-\frac{P_V}{E_V}\left(\frac{m_{\Lambda_b}+m_\Lambda}{E_\Lambda+m_\Lambda}F^-(q^2)+2F_2(q^2)\right); & (\lambda_\Lambda,\lambda_V)=(\frac{1}{2},0)\ , \\
\frac{1}{\sqrt{2}}\left(\frac{P_V}{E_\Lambda+m_\Lambda}F^-(q^2)+F^+(q^2)\right); & (\lambda_\Lambda,\lambda_V)=(-\frac{1}{2},- \\
\frac{1}{\sqrt{2}}\left(\frac{P_V}{E_\Lambda+m_\Lambda}F^-(q^2)-F^+(q^2)\right); & (\lambda_\Lambda,\lambda_V)=(\frac{1}{2},1)\ , \\
\left(F^+(q^2)+\frac{P_V^2}{E_V(E_V+m_\Lambda)}F^-(q^2)\right); & (\lambda_\Lambda,\lambda_V)=(-\frac{1}{2},0)
\end{cases} \quad (12)
$$

with $\quad F^{\pm}(q^2) \ = \ F_1(q^2) \pm F_2(q^2)$

Details and Numerical Values can be found in our last publication, hep-ph/0602043.

IV- Physical Results

1 - Branching Ratios

$$\Gamma(\Lambda_b \to \Lambda V) = \frac{E_\Lambda + M_\Lambda}{M_{\Lambda_b}} \frac{P_V}{16\pi^2} \int_\Omega |A_0(M_i)|^2 d\Omega \tag{13}$$

- Effective Number of Color, N_c^{eff} , free (Factorization Hypothesis).

N_c^{eff}	2	2.5	3	3.5
$\Lambda_b \to \Lambda J/\psi$	8.95×10^{-4}	2.79×10^{-4}	0.62×10^{-4}	0.03×10^{-4}
$\Lambda_b \to \Lambda \rho^0$	1.62×10^{-7}	1.89×10^{-7}	2.2×10^{-7}	2.4×10^{-7}
$\Lambda_b \to \Lambda \omega$	22.3×10^{-7}	4.75×10^{-7}	0.2×10^{-7}	0.64×10^{-7}

Experimental Branching Ratios (PDG, 2004)

$\mathcal{BR}^{exp}(\Lambda_b \to \Lambda J/\psi) = (4.7 \pm 2.1 \pm 1.9) \times 10^{-4}$.

$$\Longrightarrow \quad 2.0 \ \leq \ N_c^{eff} \leq \ 3.0$$

2 - Helicity Asymmetry

- Polarization $\mathcal{P}$,
- Polarization Density Matrix (PDM) elements,
- Asymmetry parameters deduced from the full calculation of the decay probability.

$\Lambda_b \to \Lambda V(1^-)$

$$\alpha_{AS}^{\Lambda_b}(\Lambda\rho^0 - \omega) = 19.4\% \ , \ \alpha_{AS}^{\Lambda_b}(\Lambda J/\psi) = 49.0\%$$

$\Lambda \to p\pi$

$$W_1(\theta_1, \phi_1) \propto 1 + \mathcal{P}^{\Lambda}\alpha_{AS}^{\Lambda}\cos\theta_1 - \frac{\pi}{2}\mathcal{P}^{\Lambda_b}\alpha_{AS}^{\Lambda}\Re e\left[\rho_{ij}^{\Lambda}\exp\left(i\phi_1\right)\right]\sin\theta_1 \qquad (14)$$

with

$$\begin{aligned} \mathcal{P}^{\Lambda} &= -0.167 \ , \quad \rho_{+-}^{\Lambda} = \quad 0.25 \quad (J/\psi) \ , \\ \mathcal{P}^{\Lambda} &= -0.21 \ , \quad \rho_{+-}^{\Lambda} = \quad 0.31 \quad (\rho^0(\omega)) \ . \end{aligned} \qquad (15)$$

$V(1^-) \to \ell^+\ell^-\ ,\ h^+h^-$

• Angular Distributions of $\ell^\pm\ ,\ h^\pm$ in $V(1^-)$ rest-frame depend on the PDM element ρ_{00}^V.

$$\rho_{00}^{J/\psi} = 0.66 \quad \text{and} \quad \rho_{00}^{\rho} = 0.79$$

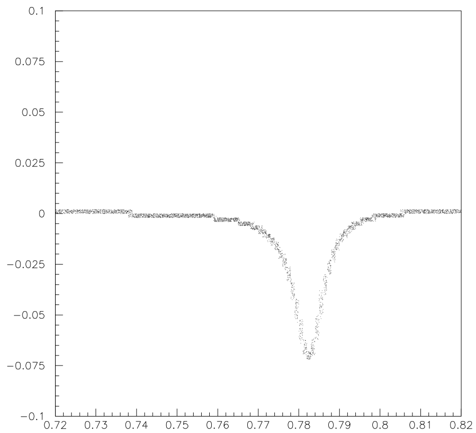
$$V \to \ell^+\ell^-$$

$$\frac{dN}{d\cos\theta_2} \propto \ (1 - 3\rho_{00}^V)\cos^2\theta_2 \ + \ (1 + \rho_{00}^V) \tag{16}$$

$$V \to \pi^+\pi^-$$

$$\frac{dN}{d\cos\theta_2} \propto \ (3\rho_{00}^V - 1)\cos^2\theta_2 \ + \ (1 - \rho_{00}^V) \tag{17}$$

3 - Effects of $\rho^0 - \omega$ Mixing



⋆ Asmmetry parameter, $a_{CP}(s_\rho)$, between two conjugated channels :

$$a_{CP}(s_\rho) = \frac{\mathcal{BR}(\Lambda_b) - \mathcal{BR}(\bar{\Lambda}_b)}{\mathcal{BR}(\Lambda_b) + \mathcal{BR}(\bar{\Lambda}_b)} . \tag{18}$$

∗ $s_\rho = \pi^+\pi^-$ Invariant Mass.

∗ At the ω mass, Asymmetry $\approx$ 7.5% for $N_c^{eff} = 3.0$

∗ Amplification of the Direct CP Violation between Λ_b and $\bar{\Lambda}_b$ because of strong phase δ_S passing through $90°$ at the ω mass.

4- Time-Odd Observables

- Laboratory Transversity Frame $\Longrightarrow$ Resonance Local Frame

$$\vec{e_1}\ ,\ \vec{e_2}\ ,\ \vec{e_3}\ \Longrightarrow\ \vec{e_X}\ ,\ \vec{e_Y}\ ,\ \vec{e_Z}$$

- Transverse Basis in Resonance rest-frame : (Jackson, 1965)

$$\vec{p} = \vec{p}_\Lambda \ \text{ or } \ \vec{p_V}, \quad \vec{e}_L = \frac{\vec{p}}{p}\ , \quad \vec{e}_T = \frac{\vec{e}_Z \times \vec{e}_L}{|\vec{e}_Z \times \vec{e}_L|}\ , \quad \vec{e}_N = \vec{e}_T \times \vec{e}_L\ . \tag{19}$$

Resonance Vector-Polarization

$$\vec{\mathcal{P}}^{(i)} = P_L{}^{(i)}\vec{e}_L + P_N{}^{(i)}\vec{e}_N + P_T{}^{(i)}\vec{e}_T\ , \tag{20}$$

with

$$P_j^{(i)} = \vec{\mathcal{P}}^{(i)} \cdot \vec{e}_j \quad \text{with} \quad j = L, N, T$$

.

- Transformation under Parity and Time Reversal

Observable	Parity	TR
$\vec{s}$	Even	Odd
$\vec{\mathcal{P}}$	Even	Odd
$\vec{e_Z}$	Even	Even
$\vec{e_L}$	Odd	Odd
$\vec{e_T}$	Odd	Odd
$\vec{e_N}$	Even	Even
P_L	Odd	Even
P_T	Odd	Even
P_N	Even	ODD

- If Normal Polarization $P_N \neq 0 \;\Rightarrow$ Sign of TR Violation.

Special Angles

$*$ $\vec{n}_\Lambda$ and $\vec{n}_V$ unit vectors normal respectively to Λ and V decay planes.

$$\vec{n}_\Lambda = \frac{\vec{p}_p \times \vec{p}_\pi}{|\vec{p}_p \times \vec{p}_\pi|} \ , \quad \vec{n}_V = \frac{\vec{p}_{l^+} \times \vec{p}_{l^-}}{|\vec{p}_{l^+} \times \vec{p}_{l^-}|} \ , \quad \text{or} \quad \vec{n}_V = \frac{\vec{p}_{h^+} \times \vec{p}_{h^-}}{|\vec{p}_{h^+} \times \vec{p}_{h^-}|} \ . \tag{21}$$

$\Longrightarrow$ Vectors which are EVEN under TR.

BUT...

Cosine and Sine of their Azimuthal Angles :

$\phi_{\vec{n}_\Lambda}$ and $\phi_{\vec{n}_V}$ (or $\phi_{(n_i)}$)

$$\vec{u}_i = \frac{\vec{e}_Z \times \vec{n}_i}{|\vec{e}_Z \times \vec{n}_i|} \ , \quad \cos\phi_{(n_i)} = \vec{e}_Y \cdot \vec{u}_i \ , \quad \sin\phi_{(n_i)} = \vec{e}_Z \cdot (\vec{e}_Y \times \vec{u}_i) \ , \quad \vec{n}_i = \vec{n}_\Lambda \ , \ \vec{n}_V \ , ($$

$\Downarrow \Downarrow \Downarrow$

$\cos\phi_{(n_i)}$, $\sin\phi_{(n_i)}$ are ODD by TR

• Those asymmetries depend on the Λ Azimuthal angle distribution in Λ_b rest-frame :

$$d\sigma/d\phi \;\propto\; 1+\frac{\pi}{2}\alpha_{AS}\Big(\Re e(\rho_{+-}^{\Lambda_b})\cos\phi-\Im m(\rho_{+-}^{\Lambda_b})\sin\phi\Big)\;, \tag{23}$$

⋆ Conservative values of non-diagonal elements of Λ_b PDM :
$\Re e(\rho_{+-}^{\Lambda_b}) = -\Im m(\rho_{+-}^{\Lambda_b}) = \sqrt{2}/2.$

$$\begin{aligned} \Lambda_b \to \Lambda J/\psi\;; &\quad AS(\cos\phi_{\vec{n}_\Lambda}) = 4.3\%\;,\;\; AS(\sin\phi_{\vec{n}_\Lambda}) = -5.5\%\;, \\ \Lambda_b \to \Lambda\rho^0(\omega)\;; &\quad AS(\cos\phi_{\vec{n}_\Lambda}) = 2.4\%\;,\;\; AS(\sin\phi_{\vec{n}_\Lambda}) = -2.7\%\;. \end{aligned} \tag{24}$$

• NO Asymmetries in $\cos\phi_{\vec{n}_V}$ and $\sin\phi_{\vec{n}_V}$

$\Longrightarrow$ Possible explanation (?)

⋆ T-Odd or TRV Effects appear in processes where Parity is Violated like
$\Lambda \to p\pi^-$

⋆ T-Odd Effects Absent in $V(1^-) \to \ell^+\ell^-\;,\; h^+h^-$ where Parity is conserved.

V- Perspectives

- Complete calculations of the process $\Lambda_b \to \Lambda V(1^-)$

* Kinematics : Helicity formalism $\oplus$ Polarization Density Matrices.

* Dynamics : Factorization procedure $\oplus$ HQET (Form-Factors)

* Hadronic Matrix Elements include both : Tree $\oplus$ Penguin Diagrams.

- "Easy Implementation" in Monte-Carlo codes $\Longrightarrow$ Evet-Gen

- Framework of the Standard Model for computing T-Odd and eventually TRV effects

$\Longrightarrow$ Only unknown parameters : Polarization Density Matrix of the initial Λ_b

- "Crucial" questions :

* Is there any dynamics behind TRV ?
* Is this "dynamics" related to the Transverse Polarization of Λ_b, Λ...?

$\Downarrow \Downarrow \Downarrow$

T-Odd and/or TRV effects are real Challenges for LHC(b) experiments.

General Expressions of Angular Distributions

$$W_1(\theta_1, \phi_1) \propto \frac{1}{2}\Bigg\{(\rho^{\Lambda}_{ii} + \rho^{\Lambda}_{jj}) + (\rho^{\Lambda}_{ii} - \rho^{\Lambda}_{jj})\alpha^{\Lambda}_{AS}\cos\theta_1 - \frac{\pi}{2}\mathcal{P}_{\Lambda_b}\alpha^{\Lambda}_{AS}\Re e\Big[\rho^{\Lambda}_{ij}\exp{(i\phi_1)}\Big]\sin$$

$$W_2(\theta_2, \phi_2) \propto (\rho^{V}_{ii} + \rho^{V}_{jj})(G^{V}_{00}(\theta_2, \phi_2) + G^{V}_{\pm1\pm1}(\theta_2, \phi_2)) - \frac{\pi}{4}\mathcal{P}_{\Lambda_b}\Re e\Big[\rho^{V}_{ij}\exp{(i\phi_2)}\Big]\sin 2\theta_2 \quad (26)$$