Novel aspects of baryon-antibaryon production in e^+e^- annihilations

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Abstract.
Baryon-antibaryon decays of J/ψ and ψ' produced at an electron-positron collider are presented as a tool to study baryon properties and to test discrete symmetries. We focus on a novel aspect of this process: the transverse polarization of the produced baryons. The polarization was observed for first time by the BESIII Collaboration in $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$. The observed spin polarization and correlations were used for a direct determination the Λ and $\bar{\Lambda}$ decay asymmetries. The result for $\Lambda \to p\pi^-$, the well known Λ polarimeter process, differs by 17(3)% from the established value of 0.642(13). Finally the prospects of the method for studies of weak decays of hyperons and for CP tests in baryon sector are discussed.

1 Introduction

The well-defined and simple initial state makes baryon-antibaryon pair production at an electron-positron collider an ideal system to test fundamental symmetries in the baryon sector, in particular when the probability of the process is enhanced by a resonance such as the J/ψ [1]. The spin orientations of the baryon and antibaryon are correlated and, for spin one-half baryons, the pair is produced either with the same or opposite helicities. The transition amplitudes to the respective spin states can acquire a relative phase, $\Delta\Phi$ due to the strong interaction in the final state, leading to a time-reversal-odd observable: a transverse spin polarization of the baryons [2, 3]. This effect had been neglected in analyses of the baryon pairs from the J/ψ and ψ' decays [4, 5]. We have shown [6] that the same formalism as for the continuum baryon-antibaryon pair production in electron-positron annihilation related to the time-like baryon form factors [7–11] should be used to describe the decays. We have also derived explicit expressions for the joint angular distributions, suitable for the maximum log-likelihood fits, in $e^+e^- \to \Lambda\bar{\Lambda}$ process where the Λ and $\bar{\Lambda}$ are reconstructed using their main two body hadronic weak decays. The formalism was applied in the BESIII analysis leading to the first observation of Λ transverse polarization in $J/\psi \to \Lambda\bar{\Lambda}$ decay [12].

In the next sections we summarize the formalism, report the results of BESIII proof of concept analysis and discuss some extensions and prospects of the method.

2 Formalism

Consider $e^+e^- \to B_1\bar{B}_2$ reaction where $B_1\bar{B}_2$ is a baryon-antibaryon pair (both with spin one-half). In general, a quantum state of a fermion pair could be represented by the following

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spin density matrix:

$$\rho_{1/2,\overline{1/2}} = \sum_{\mu,\nu=0}^{3} C_{\mu\nu}\, \sigma_{\mu}^{B_1} \otimes \sigma_{\nu}^{\bar{B}_2} \ , \tag{1}$$

where the set of 2×2 base spin matrices σ_μ^B in the rest frame of a baryon B is defined as:

$$\sigma_0^B = \mathbb{1}_2\ ; \sigma_1^B = \sigma_x\ ; \sigma_2^B = \sigma_y\ ; \sigma_3^B = \sigma_z\ , \tag{2}$$

where $\mathbb{1}_2$ is 2×2 identity matrix and $\sigma_x, \sigma_y, \sigma_z$ are Pauli spin matrices. Here, as in Ref. [6], we use the same orientations of the spin quantization axes for B_1 and $\bar{B}_2$ with the z direction along B_1 momentum in the overall center-of-mass (c.m.) system of the $B_1\bar{B}_2$ pair. The y direction is given by the vector product of the incoming electron and the outgoing baryon B_1 momenta. The coefficients $C_{\mu\nu}$ depend on the angle θ between the electron and baryon B_1. At c.m. energies when electron mass could be neglected, a single photon annihilation process could only proceed if the electrons have opposite helicities. The final state baryons can have both $\pm 1/2$ helicities. Due to parity conservation out of the four possible helicity transitions only two are independent: $A_{1/2,1/2} = A_{-1/2,-1/2} =: h_1$ and $A_{1/2,-1/2} = A_{-1/2,1/2} =: h_2$ [13]. Therefore $e^+e^- \to B_1\bar{B}_2$ process at fixed c.m. energy is described by two complex form factors. If one is only interested in the not normalized angular distributions only two real parameters are needed which could be defined as:

$$\alpha_\psi := \frac{|h_2|^2 - 2|h_1|^2}{|h_2|^2 + 2|h_1|^2}\ ; -1 \le \alpha_\psi \le 1 \ \text{ and } \ \Delta\Phi := \arg(h_1/h_2). \tag{3}$$

The $C_{\mu\nu}$ 4×4 matrix is given as [6]:

$$\begin{pmatrix} 1+\alpha_\psi\cos^2\theta & 0 & \beta_\psi \sin\theta\cos\theta & 0 \\ 0 & \sin^2\theta & 0 & \gamma_\psi\sin\theta\cos\theta \\ \beta_\psi\sin\theta\cos\theta & 0 & \alpha_\psi\sin^2\theta & 0 \\ 0 & \gamma_\psi\sin\theta\cos\theta & 0 & \alpha_\psi + \cos^2\theta \end{pmatrix}, \tag{4}$$

where $\beta_\psi = \sqrt{1-\alpha_\psi^2}\sin(\Delta\Phi)$ and $\gamma_\psi = \sqrt{1-\alpha_\psi^2}\cos(\Delta\Phi)$ implying $\alpha_\psi^2 + \beta_\psi^2 + \gamma_\psi^2 = 1$. The polarization vectors $\mathbf{P}$ of B_1 and B_2 has to be in y direction and the value is given by $P_y = C_{02}/C_{00} = \beta_\psi \sin\theta\cos\theta/(1+\alpha_\psi\cos^2\theta)$.

If a baryon decays weakly, such as the ground state hyperons or charmed baryons, the polarization can be determined using angular distribution of the daughter particles. For example, for the $\Lambda \to p\pi^-$ decay with the Λ hyperon polarization given by the $\mathbf{P}$ vector, the angular distribution of the daughter protons is $\frac{1}{4\pi}(1+\alpha_-\mathbf{P}\cdot\hat{\mathbf{n}})$, where $\hat{\mathbf{n}}$ is the unit vector along the proton momentum in the Λ rest frame and α_- is the asymmetry parameter of the decay [14]. The corresponding parameters α_+ for $\bar{\Lambda} \to \bar{p}\pi^+$, α_0 for $\Lambda \to n\pi^0$, and $\bar{\alpha}_0$ for $\bar{\Lambda} \to \bar{n}\pi^0$ are defined in the same way [15]. In a general weak hadronic decay of a spin one-half baryon into a spin one-half baryon and pseudoscalar meson: $B_A \to B_B + P$, both the initial an the final states are represented by a linear combinations of the spin one-half density matrices $\sigma_\mu^{B_A}$ and $\sigma_\nu^{B_B}$ Eq. (2), respectively. One can therefore represent the weak decay by a *decay matrix*, $a_{\mu,\nu}^{B_A\to B_B+P}$, which transforms the base matrices [13]:

$$\sigma_\mu^{B_A} \to \sum_{\nu=0}^{3} a_{\mu,\nu}^{B_A\to B_B+P}\sigma_\nu^{B_B}. \tag{5}$$

In general there are two parameters to describe the $B_A \to B_B + P$ decay, in addition to the decay asymmetry, $-1 \le \alpha^{B_A\to B_B+P} \le 1$, Particle Data Group [15] uses phase $-\pi \le \phi^{B_A\to B_B+P} <$

π. If the polarization of the baryon B_B is not measured the decay is described only by the $a_{\mu,0}^{B_A\to B_B+P}$ elements of the decay matrix and only the $\alpha^{B_A\to B_B+P}$ parameter is involved. The joint angular distribution of $J/\psi \to \Lambda\bar{\Lambda}$ ($\Lambda \to f$ and $\bar{\Lambda} \to \bar{f}$, $f = p\pi^-$) can be therefore written as the trace of the final proton-antiproton density matrix:

$$\mathcal{W}(\boldsymbol{\xi};\alpha_\psi,\Delta\Phi,\alpha_-,\alpha_+) := \mathrm{Tr}(\rho_{p,\bar{p}}) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu}(\cos\theta;\alpha_\psi,\Delta\Phi)a_{\mu,0}^{\Lambda\to p\pi^-}(\hat{\mathbf{n}}_1;\alpha_-)a_{\nu,0}^{\bar{\Lambda}\to\bar{p}\pi^+}(\hat{\mathbf{n}}_2;\alpha_+). \tag{6}$$

where $\boldsymbol{\xi} := (\cos\theta,\hat{\mathbf{n}}_1,\hat{\mathbf{n}}_2)$ is the complete set of kinematical variables describing the event configuration in the five dimensional phase space and $\hat{\mathbf{n}}_1$ ($\hat{\mathbf{n}}_2$) is the unit vector in the direction of the nucleon (antinucleon) in the rest frame of Λ ($\bar{\Lambda}$). It can be written explicitly as [6]:

$$\begin{aligned}\mathcal{W}(\boldsymbol{\xi};\alpha_\psi,\Delta\Phi,\alpha_-,\alpha_+) &= C_{00} + C_{02}\cdot(\alpha_- n_{1,y} + \alpha_+ n_{2,y})\\ &+ \alpha_-\alpha_+\left\{C_{11}n_{1,x}n_{2,x} - C_{22}n_{1,y}n_{2,y} + C_{33}n_{1,z}n_{2,z} + C_{13}(n_{1,x}n_{2,z} + n_{1,z}n_{2,x})\right\}.\end{aligned} \tag{7}$$

The terms multiplied by $\alpha_-\alpha_+$ represent the contribution from the $\Lambda\bar{\Lambda}$ spin correlations, while the terms multiplied by α_- and α_+ separately represent the contribution from the polarizations. If all three contributions in Eq. (7) are non-zero an unambiguous determination of the parameters α_ψ and $\Delta\Phi$ and the decay asymmetries α_-, α_+ is possible. One should stress that the inclusive measurement of the proton momenta from the $\Lambda \to p\pi^-$ decay is not sufficient to determine uniquely α_-. Integrating Eq. (7) over the unmeasured $\bar{p}$ direction $\hat{\mathbf{n}}_2$ one gets:

$$4\pi\left(C_{00} + \alpha_-\sqrt{1-\alpha_\psi^2}\,\sin(\Delta\Phi)n_{1,y}\sin\theta\cos\theta\right), \tag{8}$$

where the polarization term is written explicitly in terms of $\Delta\Phi$. It is clear that only the product $\alpha_-\cdot\sin(\Delta\Phi)$ can be determined from such inclusive analysis.

3 Observation of polarization in $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$ at BESIII [12]

The BESIII Collaboration has carried out an analysis of $e^+e^- \to J/\psi \to \Lambda\bar{\Lambda}$ based on 1.31×10^9 J/ψ events collected with the BESIII detector [12]. The Λ hyperons are reconstructed using their $p\pi^-$ decays and the $\bar{\Lambda}$ hyperons using their $\bar{p}\pi^+$ or $\bar{n}\pi^0$ decays. The sizes of the final data samples are 420,593 and 47,009 events with an estimated background of 399 ± 20 and 66.0 ± 8.2 events for the $p\pi^-\bar{p}\pi^+$ and $p\pi^-\bar{n}\pi^0$ final states, respectively. The background contribution is determined from Monte Carlo (MC) simulation including all known J/ψ decays. For each event the full set of the kinematic variables $\boldsymbol{\xi}$ is reconstructed. The free parameters describing the angular distributions for the two data sets — α_ψ, $\Delta\Phi$, α_-, α_+, and $\bar{\alpha}_0$ — are determined from a simultaneous unbinned maximum likelihood fit using angular distribution given by Eq. (7). A clear polarization signal, strongly dependent on the Λ direction, $\cos\theta$, is observed for Λ and $\bar{\Lambda}$. In Fig. 1(a) the moment $\mu(\cos\theta) = (m/N)\ \sum_i^{N_k}(n_{1,y}^{(i)} - n_{2,y}^{(i)})$ related to the polarization is calculated for $m = 50$ bins in $\cos\theta$. N is the total number of events in the data sample and N_k is the number of events in k-th $\cos\theta$ bin. The expected angular dependence is $\mu(\cos\theta) \sim (\alpha_- - \alpha_+)\cdot C_{02}$ for the acceptance corrected data (compare Eq. (7)). The phase between helicity flip and helicity conserving transitions is determined to be $\Delta\Phi = (42.4\pm0.6\pm0.5)^\circ$. This value of the phase corresponds to the polarization P_y as shown in Fig. 1(b) reaching maximum of 25%. This large value of the phase enables a simultaneous determination of the decay asymmetry parameters for $\Lambda \to p\pi^-$, $\bar{\Lambda} \to \bar{p}\pi^+$, and $\bar{\Lambda} \to \bar{n}\pi^0$ as given in Table 1. The value of $\alpha_- = 0.750\pm0.009\pm0.004$ differs by more than five standard deviations from the world average value of $\alpha_-^{\mathrm{PDG}} = 0.642\pm0.013$ established in

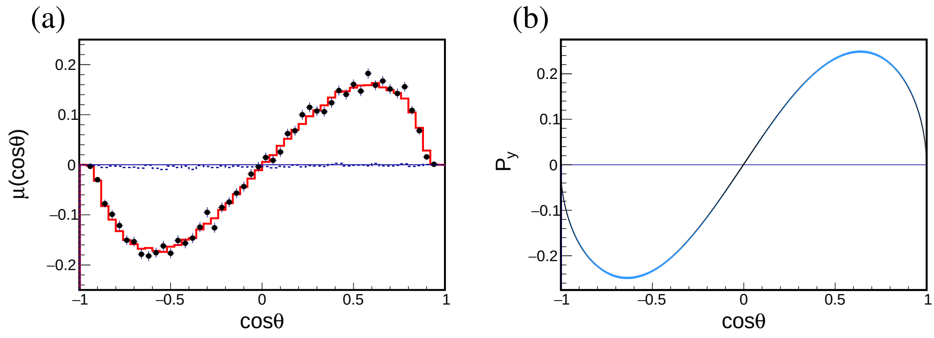

Figure 1. (a) Moment $\mu(\cos\theta)$ as a function of $\cos\theta$ for $e^+e^- \to J/\psi \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$. The points with error bars are the BESIII data, and the solid-line histogram is the global fit results. The dashed histogram shows the no polarization scenario ($\mathcal{W}(\xi; 0,0,0,0) \equiv 1$). (b) Polarization of Λ as a function of $\cos\theta$ calculated using the determined values of α_ψ and $\Delta\Phi$.

Table 1. Summary of the results: the $J/\psi \to \Lambda\bar{\Lambda}$ angular distribution parameter α_ψ, the phase $\Delta\Phi$, the asymmetry parameters for the $\Lambda \to p\pi^-$ (α_-), $\bar{\Lambda} \to \bar{p}\pi^+$ (α_+) and $\bar{\Lambda} \to \bar{n}\pi^0$ ($\bar{\alpha}_0$) decays, the CP asymmetry A_Λ, and the ratio $\bar{\alpha}_0/\alpha_+$.

Parameters	BESIII	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 [16]
$\Delta\Phi$	$(42.4 \pm 0.6 \pm 0.5)^\circ$	–
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 [15]
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 [15]
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	–
A_Λ	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 [15]
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	–

Table 2. Expected statistical uncertainties for A_Λ from future measurements.

Experiment	Events	Stat. error ΔA_Λ	Comment
BESIII(2018)	$4.2 \cdot 10^5$	$1.2 \cdot 10^{-2}$	$1.3 \cdot 10^9 J/\psi$
BESIII	$3.2 \cdot 10^6$	$4 \cdot 10^{-3}$	$10^{10} J/\psi$
STCF	$6 \cdot 10^8$	$3 \cdot 10^{-4}$	$2 \cdot 10^{12} J/\psi$

1978 [17]. However, in our opinion the uncertainty on α_-^{PDG} should be larger since it does not include *e.g.* a systematic uncertainty of at least 5% for the two most precise results [18, 19]. Our value implies that all published measurements of the $\Lambda/\bar{\Lambda}$ polarization should be reduced by $(17 \pm 3)\%$. Since the correlation coefficient between α_- and α_+ is large (0.82) the average value of α_- assuming CP conservation is very precise: $(\alpha_- - \alpha_+)/2 = 0.754(3)$, where only the statistical uncertainty is given.

4 Outlook

The CP test using $A_\Lambda := (\alpha_- + \alpha_+)/(\alpha_- - \alpha_+)$ asymmetry can be significantly improved with full data sample of $10^{10} J/\psi$ collected already at BESIII see Table 2. At the planned Supper Tau Charm Factories (STCF) the expected number of produced J/ψ could increase by factor of 200 – 500 and the sensitivity of A_Λ will be close to the Cabibbo-Kobayashi-Maskawa mechanism predictions of $A_\Lambda \sim (1-5)\cdot 10^{-5}$ [20].

For the double strange baryon-antibaryon pair production like Ξ^0 and Ξ^-: $e^+e^- \to J/\psi \to \Xi\bar{\Xi}$ with two chains of sequential decays $\Xi \to \pi(\Lambda \to f) + c.c.$ the application of Eqs. (1) and (5) leads to the following joint angular distribution in the nine dimensional phase space [13]:

$$\mathrm{Tr}(\rho_{p,\bar{p}}) = \sum_{\mu,\nu=0}^{3} C_{\mu\nu} \sum_{\mu',\nu'=0}^{3} a_{\mu,\mu'}^{\Xi\to\Lambda\pi} a_{\nu,\nu'}^{\bar{\Xi}\to\bar{\Lambda}\pi} a_{\mu',0}^{\Lambda\to p\pi^-} a_{\nu',0}^{\bar{\Lambda}\to\bar{p}\pi^+}. \tag{9}$$

This is much more complicated formula than for the $J/\psi \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$ case and it involves eight global parameters. Two parameters describe the $e^+e^- \to J/\psi \to \Xi\bar{\Xi}$ reaction spin density matrix (α_ψ and $\Delta\Phi$), two are needed to specify each of the $a_{\mu,\mu'}^{\Xi\to\Lambda\pi}$ and $a_{\nu,\nu'}^{\bar{\Xi}\to\bar{\Lambda}\pi}$ decay matrices (since the polarization of $\Lambda(\bar{\Lambda})$ is measured), α_- and α_+. One can rewrite the angular distributions from Eq. (6) and Eq. (9) as a sum of terms consisting of products of functions of the global parameters ($\boldsymbol{\pi}$) and the kinematic variables ($\boldsymbol{\xi}$):

$$\sum_{k=1}^{M} g_k(\boldsymbol{\pi}) \cdot h_k(\boldsymbol{\xi}). \tag{10}$$

Such representation for the angular distribution in Eq. (9) requires $M = 72$ unique functions $g_k(\boldsymbol{\pi})$ of the global parameters while Eq. (6) only $M = 7$. If $\Delta\Phi = 0$ the number of such terms reduces to $M = 56$ in Eq. (9), therefore likely all the decay parameters can be determined even if $\Delta\Phi = 0$ (depending whether other parameters are zero).

In our Ref. [13] a formalism for spin-3/2 baryons, which can be used to describe *e.g.* reaction $e^+e^- \to \psi' \to \Omega^-\bar{\Omega}^+$ with the subsequent decays, is also given.

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