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Hyperon studies at BESIII

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Recent results on $e^+e^- \to \Lambda\bar{\Lambda}$ from BESIII Collaboration are reported: (i) for the process at J/ψ and (ii) for the non-resonant production.
(i) Using a data sample of 1.31×10^9 J/ψ events we report the first observation of spin polarization of Λ and $\bar{\Lambda}$ hyperons. The phase between the helicity flip and helicity non-flip amplitudes of $\Delta\Phi = (42.4 \pm 0.6 \pm 0.5)^\circ$ is determined. The decay asymmetries for $\Lambda \to p\pi^-$ (α_-), $\bar{\Lambda} \to \bar{p}\pi^+$ (α_+) and $\bar{\Lambda} \to \bar{n}\pi^0$ ($\bar{\alpha}_0$) are measured to be $\alpha_- = 0.750 \pm 0.009 \pm 0.004$, $\alpha_+ = -0.758 \pm 0.010 \pm 0.007$ and $\bar{\alpha}_0 = -0.692 \pm 0.016 \pm 0.006$, respectively. The obtained value of α_- is higher by $(17 \pm 3)\%$ than the world average of 0.642 ± 0.013 used for all Λ polarization measurements since 1978. The CP asymmetry $A_{CP} = (\alpha_- + \alpha_+)/(\alpha_- - \alpha_+)$ of $-0.006 \pm 0.012 \pm 0.007$ and the ratio $\bar{\alpha}_0/\alpha_+ = 0.913 \pm 0.028 \pm 0.012$ are also measured.
(ii) Using 66.9 pb^{-1} collected at $\sqrt{s} = 2.396$ GeV Λ form factors are determined. This is the first complete determination of the time-like elastic form factors G_M and G_E for any baryon: the ratio $R = |G_E/G_M|$ and the relative phase $\Delta\Phi = \arg(G_E/G_M)$. Using the decay asymmetry parameters from analysis (i) as input, the obtained values are $R = 0.96 \pm 0.14 \pm 0.02$ and $\Delta\Phi = (37 \pm 12 \pm 6)^\circ$, respectively. The normalization of the form factors is set by the determined Born cross section cross section of $\sigma_{Born} = 119.0 \pm 5.3 \pm 5.1$ pb.
In a separate analysis a surprisingly large Born cross section of $305 \pm 45^{+66}_{-36}$ pb is measured at $\sqrt{s}$=2.2324 GeV, which is 1.0 MeV above the threshold.

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1. The $e^+e^- \to \Lambda\bar{\Lambda}$ process at the J/ψ resonance ([1, 2])

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 [3]. 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 [4, 5]. This effect has no prediction and was previously neglected for the baryon pairs from J/ψ decays [6].

The polarization of the Λ hyperons, can be determined using the angular distribution of the daughter particles. For example, for the $\Lambda \to p\pi^-$ decay with the Λ hyperon polarization given by the $\mathbf{P}_\Lambda$ vector, the angular distribution of the daughter protons is $\frac{1}{4\pi}(1+\alpha_- \mathbf{P}_\Lambda \cdot \hat{\mathbf{n}})$, 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 [7]. 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 [8]. The joint angular distribution of $J/\psi \to \Lambda\bar{\Lambda}$ ($\Lambda \to f$ and $\bar{\Lambda} \to \bar{f}$, $f = p\pi^-$ or $n\pi^0$) depends on the Λ and $\bar{\Lambda}$ polarization and spin correlation of the $\Lambda\bar{\Lambda}$ pair via the α_ψ and $\Delta\Phi$ parameters. In particular, the joint angular distribution of the decay chain $J/\psi \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$ can be expressed as [6]:

$$\begin{aligned}
&\mathscr{W}(\boldsymbol{\xi};\alpha_\psi,\Delta\Phi,\alpha_-,\alpha_+) = 1+\alpha_\psi \cos^2\theta \\
&+\alpha_-\alpha_+\left\{\sin^2\theta\left(n_{1,x}n_{2,x}-\alpha_\psi n_{1,y}n_{2,y}\right)+\left(\cos^2\theta+\alpha_\psi\right)n_{1,z}n_{2,z}+\sqrt{1-\alpha_\psi{}^2}\cos\Delta\Phi\sin 2\theta\,\frac{n_{1,x}n_{2,z}+n_{1,z}n_{2,x}}{2}\right\} \\
&+\sqrt{1-\alpha_\psi{}^2}\sin(\Delta\Phi)\,\sin\theta\cos\theta\left(\alpha_- n_{1,y}+\alpha_+ n_{2,y}\right),
\end{aligned} \tag{1.1}$$

where $\hat{\mathbf{n}}_1$ ($\hat{\mathbf{n}}_2$) is the unit vector in the direction of the nucleon (antinucleon) in the rest frame of Λ ($\bar{\Lambda}$). The components of these vectors are expressed using a common coordinate system defined in Ref. [2]. The terms multiplied by $\alpha_-\alpha_+$ represent the contribution from $\Lambda\bar{\Lambda}$ spin correlations, while the terms multiplied by α_- and α_+ separately represent the contribution from the polarizations. If all three contributions in Eq. (1.1) are non-zero an unambiguous determination of the parameters α_ψ and $\Delta\Phi$ and the decay asymmetries α_-, α_+ is possible.

The analysis is based on 1.31×10^9 J/ψ events collected with the BESIII detector. 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. (1.1). A clear polarization, strongly dependent on the Λ direction, $\cos\theta$, is observed for Λ and $\bar{\Lambda}$. In Fig. 1, 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 $\mu(\cos\theta) \sim \sqrt{1-\alpha_\psi^2}(\alpha_- - \alpha_+)\sin\Delta\Phi\cos\theta\sin\theta$ for the acceptance corrected data (compare

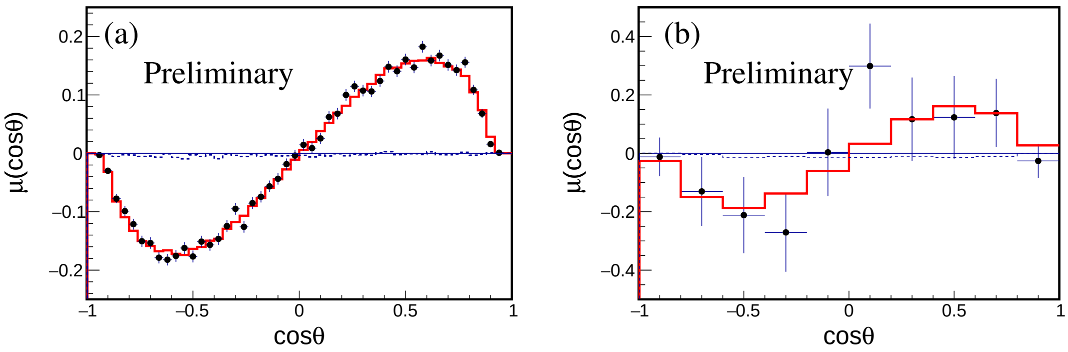

Figure 1: Moments $\mu(\cos\theta)$ as a function of $\cos\theta$ for $e^+e^- \to (\Lambda \to p\pi^-)(\bar{\Lambda} \to \bar{p}\pi^+)$ data samples at (a) $\sqrt{s} = 3.096$ GeV (J/ψ mass) and (b) $\sqrt{s} = 2.396$ GeV. The points with error bars are the data, and the solid-line histograms are the global fit results. The dashed histograms show the no polarization scenario ($\mathscr{W}(\boldsymbol{\xi};0,0,0,0) \equiv 1$).

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_{CP}, and the ratio $\bar{\alpha}_0/\alpha_+$.

Parameters	This work	Previous results
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 [1]
$\Delta\Phi$	$(42.4 \pm 0.6 \pm 0.5)^\circ$	–
α_-	$0.750 \pm 0.009 \pm 0.004$	0.642 ± 0.013 [8]
α_+	$-0.758 \pm 0.010 \pm 0.007$	-0.71 ± 0.08 [8]
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	–
A_{CP}	$-0.006 \pm 0.012 \pm 0.007$	0.006 ± 0.021 [8]
$\bar{\alpha}_0/\alpha_+$	$0.913 \pm 0.028 \pm 0.012$	–

Eq. (1.1)). The phase between helicity flip and helicity conserving transitions is determined to be $\Delta\Phi = (42.4 \pm 0.6 \pm 0.5)^\circ$. 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 $\alpha_- = 0.750 \pm 0.009 \pm 0.004$ differs by more than five standard deviations from the world average value of $\alpha_-^{\mathrm{PDG}} = 0.642 \pm 0.013$ established in 1978 [9]. 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% in the two most precise results [10, 11]. Our value implies that all published measurements on $\Lambda/\bar{\Lambda}$ polarization are $(17 \pm 3)\%$ too large.

2. The $e^+e^- \to \Lambda\bar{\Lambda}$ process at the continuum ([12] and preliminary)

In a run at $\sqrt{s} = 2.396$ GeV with integrated luminosity of 66.9 pb^{-1} a data sample of 555 $e^+e^- \to \Lambda\bar{\Lambda}$ ($\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$) candidate events was collected. The estimated background is 14 ± 4. This allows measurement of Λ hyperon form factors, the first complete determination of time-like elastic form factors (EFFs) for any baryon. In the analysis the joint angular distribution given by Eq. (1.1) is used. The helicity non-flip and flip amplitudes are identified with the electric and magnetic form factors G_E and G_M, respectively. The complete information about the form factors is represented by the Born cross section, the ratio $R = |G_E/G_M|$ and the phase $\Delta\Phi = \arg(G_E/G_M)$. Using the values for the decay asymmetry parameters α_- and α_+ from the BESIII analysis described in Sec. 1 as the input, the obtained values are: $R = 0.96 \pm 0.14 \pm 0.02$ and $\Delta\Phi = (37 \pm 12 \pm 6)^\circ$. The observed non-zero phase is a clear demonstration that the Λ EFFs cannot be described by rational functions of the four-momentum transfer squared [5]. The Born cross section of the process is measured to be $119.0 \pm 5.3 \pm 5.1$ pb.

In a sepatate analysis the Born cross section for the process $e^+e^- \to \Lambda\bar{\Lambda}$ was measured at $\sqrt{s} = 2.2324$ GeV [12], i.e. 1.0 MeV above threshold, to be $305 \pm 45^{+66}_{-36}$ pb. Such large value is unexpected since for neutral baryons the cross section is not enhanced by the Coulomb factor and should vanish at threshold.

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