

## $\Lambda$ hyperon spin polarization and CP tests at BESIII

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**Abstract.** In these proceedings two preliminary results from the BESIII collaboration on polarized  $\Lambda$  and  $\bar{\Lambda}$  are reported. Both results are first observations and concern the resonant and non-resonant processes  $e^-e^+ \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}$  and  $e^-e^+ \rightarrow \gamma^* \rightarrow \Lambda\bar{\Lambda}$  at  $\sqrt{s} = 2.396$  GeV, respectively. For  $J/\psi \rightarrow \Lambda\bar{\Lambda}$  the relative phase between the electric and magnetic form factors,  $\Delta\Phi$ , has for the first time been determined,  $\Delta\Phi = 42.4(6)_{\text{stat}}(5)_{\text{syst}}^\circ$ . That  $\Delta\Phi \neq 0$  allows for a simultaneous measurement also of the asymmetry decay parameters  $\Lambda \rightarrow p\pi^-$  ( $\alpha_-$ ),  $\bar{\Lambda} \rightarrow \bar{p}\pi^+$  ( $\alpha_+$ ) and  $\bar{\Lambda} \rightarrow \bar{n}\pi^0$  ( $\bar{\alpha}_0$ ). The measured value of  $\alpha_- = 0.750 \pm 0.009 \pm 0.004$  differs by 17(3)% from the PDG value. The simultaneous measurement for the asymmetry parameters allows for the most precise test of CP violation conducted for  $\Lambda$  decays,  $A_{\text{CP}} = -0.006(12)_{\text{stat}}(7)_{\text{syst}}$ . The reaction  $e^-e^+ \rightarrow \Lambda\bar{\Lambda}$  at  $\sqrt{s} = 2.396$  GeV is the first complete measurement of the time-like electric ( $G_E$ ) and magnetic ( $G_M$ ) form factor of any baryon as also the ratio  $R = |(G_E/G_M)|$  and  $\Delta\Phi$  have been determined:  $R = 0.96(14)(12)$  and  $\Delta\Phi = 37(12)_{\text{stat}}(6)_{\text{syst}}^\circ$ . The obtained cross-section and effective form factor are  $\sigma = 119.0(53)_{\text{stat}}(51)_{\text{syst}}$  pb and  $|G| = 0.123(3)_{\text{stat}}(3)_{\text{syst}}$ , respectively.

### 1 Introduction

The electromagnetic form factors (EMFF) are basic hadron structure observables related to the charge and magnetization density of the hadron and are currently the best way to study hyperon ( $Y$ ) structure. In the time-like region, the EMFF's can be complex with a relative phase. A non-zero phase polarizes the final state even when the initial state is unpolarized. Hyperons also have the advantage compared to protons that their polarization is experimentally accessible by the angular distributions of their decay products. A dedicated data sample collected by the BESIII experiment for this purpose provides new insights. If hyperons are produced in a polarized state, direct tests of CP symmetry are possible by simultaneously measuring angular distributions of hyperons and anti-hyperons ( $\bar{Y}$ ). This can be done e.g. via the process  $e^+e^- \rightarrow J/\psi \rightarrow Y\bar{Y}$ . BESIII has collected the world's largest  $J/\psi$  data sample with an ongoing experimental campaign to further increase the statistics. In addition, due to symmetric, excellent detector conditions and low hadronic background the experiment offers a clean environment for CP-violation tests using  $Y\bar{Y}$ .

A peculiarity of the time-like EMFF's is that the final state baryons can be polarized even if the initial state is unpolarized [1, 2]. This is because intermediate virtual hadron-antihadron states polarize the final state particles. The electric ( $G_E$ ) and magnetic ( $G_M$ ) form factors can

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therefore be complex,  $G_E = |G_E| \times e^{i\Phi_E}$  and  $G_M = |G_M| \times e^{i\Phi_M}$ . If the relative phase between  $G_E$  and  $G_M$  is non-zero,  $\Delta\Phi = \Phi_E - \Phi_M$ , the final state baryons are spin-polarized. The spin-polarization is experimentally accessible when studying weak, parity violating hyperon decays. The reason is that hyperons are self analyzing, meaning that the daughter particles are emitted according to the polarization of the mother hyperon.

## 1.1 Formalism

The EMFFs are studied by considering their response at different four-momentum squared,  $q^2$ , and different kinematical regions can be studied in space- ( $q^2 < 0$ ) and time-like ( $q^2 > 0$ ) processes. The space-like region is studied in electron-baryon scattering processes, of the type  $e^-B \rightarrow e^-B$ , while the time-like region can be accessed in e.g. annihilation processes,  $e^-e^+ \rightarrow B\bar{B}$ . In the scenario where the spin-1/2 hyperon-antihyperon pair, here being  $\Lambda\bar{\Lambda}$ , is produced and decays through  $e^-e^+ \rightarrow J/\psi \rightarrow \Lambda(\rightarrow p\pi^-)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$ , the full process can be described by combining and folding the production and decay process [4]. The differential cross-section is described by five measured observables  $\xi = (\theta_\Lambda, \theta_1, \phi_1, \theta_2, \phi_2)$ , where  $\theta_\Lambda$  is the angle between  $\Lambda$  and the positron in the reaction center-of-mass frame, and the other four are the daughter baryon angles given in the so-called helicity frame. The helicity frame is defined with respect to the  $\Lambda$  and  $\bar{\Lambda}$  rest frames [5]. The differential cross-section is given by  $d\sigma \propto \mathcal{W}(\xi)d\xi$ , where  $\mathcal{W}(\xi)$  is

$$\begin{aligned} \mathcal{W}(\xi) = & \mathcal{T}_0 + \eta\mathcal{T}_5 + \alpha_-\alpha_+ \left( \mathcal{T}_1 + \sqrt{1-\eta^2} \cos(\Delta\Phi)\mathcal{T}_2 + \eta\mathcal{T}_6 \right) \\ & + \sqrt{1-\eta^2} \sin(\Delta\Phi) (\alpha_-\mathcal{T}_3 + \alpha_+\mathcal{T}_4), \end{aligned} \quad (1)$$

and the functions  $\mathcal{T}_i$  only depend on  $\xi$ . The parameters to be determined are the angular distribution parameter  $\eta$ , the relative phase  $\Delta\Phi$ , and the asymmetry decay parameters,  $\alpha$ . The asymmetry decay parameters for  $\Lambda \rightarrow p\pi^-$ ,  $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ ,  $\Lambda \rightarrow n\pi^0$  and  $\bar{\Lambda} \rightarrow \bar{n}\pi^0$  are denoted by  $\alpha_-$ ,  $\alpha_+$ ,  $\alpha_0$  and  $\bar{\alpha}_0$ , respectively. If baryon-antibaryon symmetry holds, then the hyperon asymmetry parameter is equal and opposite to the CP-odd anti-hyperon,  $\alpha_- = -\alpha_+$ . To test CP symmetry the observable  $A_{CP}$  can be measured,  $A_{CP} = (\alpha_- + \alpha_+)/(\alpha_- - \alpha_+)$  with  $A_{PDG} = 0.006(21)$  [3].  $\eta$  can also be expressed as  $\eta = \frac{\tau-R^2}{\tau+R^2}$ , where  $\tau$  is a kinematical factor and  $R$  is the form factor ratio  $|G_E/G_M|$ . The formula in eqn. (1) contains three types of terms: the scattering angle of  $\Lambda$  ( $\mathcal{T}_0 + \eta\mathcal{T}_5$ ), spin correlations (terms multiplied by  $\alpha_-\alpha_+$ ) and separate polarization terms (the terms multiplied by  $\sqrt{1-\eta^2} \sin(\Delta\Phi)$ ). Only when  $\Delta\Phi \neq 0$  can all parameters be determined individually and simultaneously and only then can a direct measurement of  $A_{CP}$  be performed.

## 1.2 Previous experiments

Much experimental effort has been put into the study of nucleon pair production and their form factors in the time-like region [6], but the corresponding hyperon EMFF's have not been well explored. Concerning the  $\Lambda\bar{\Lambda}$  Born cross-section it has previously been studied by the BaBar [7] and DM2 [8] collaborations. Recently also BESIII published results based on data sets taken at  $\sqrt{s} = 2.2324, 2.400, 2.800, 3.080$  GeV [16]. The lowest energy point is only 1.0 MeV above the production threshold and the cross section at  $\sqrt{s} = 2.2324$  is determined to be  $305(45)_{\text{stat}}(^{+66}_{-36})_{\text{sys}}$  pb. The Born cross-sections for the other three data points are in good agreement but more precise than the BaBar [7] and DM2 [8] results. There has been

no experimental determination of  $\Lambda$  polarization for the time-like EMFF. There is, however, a theoretical prediction [9], which has used PS185 data [10] from  $p\bar{p} \rightarrow \Lambda\bar{\Lambda}$  as constraint. At the  $J/\psi$  resonance there has been no determination of  $\Delta\Phi$  for  $\Lambda\bar{\Lambda}$  even though  $\eta$  has been determined several times [11–13].

## 2 BESIII experiment and data samples

In these proceedings two new preliminary results from the BESIII collaboration are presented. The results are based on data taken with the BESIII magnetic spectrometer [14] located at the Beijing Electron Positron Collider (BEPCII) [15], Beijing, China. The process  $J/\psi \rightarrow \Lambda\bar{\Lambda}$  has been analyzed from a collected sample of  $(1310.6 \pm 7.0) \times 10^6$   $J/\psi$  events [17]. The EMFF of  $e^+e^- \rightarrow \Lambda\bar{\Lambda}$  at  $\sqrt{s} = 2.396$  GeV has been measured from an exclusive reconstruction of the final state particles  $p, \bar{p}, \pi^-$  and  $\pi^+$ . The final event sample consists of 555 events where  $14 \pm 4$  events are estimated to be background.

## 3 Results

### 3.1 Asymmetry parameter measurement of $\Lambda\bar{\Lambda}$

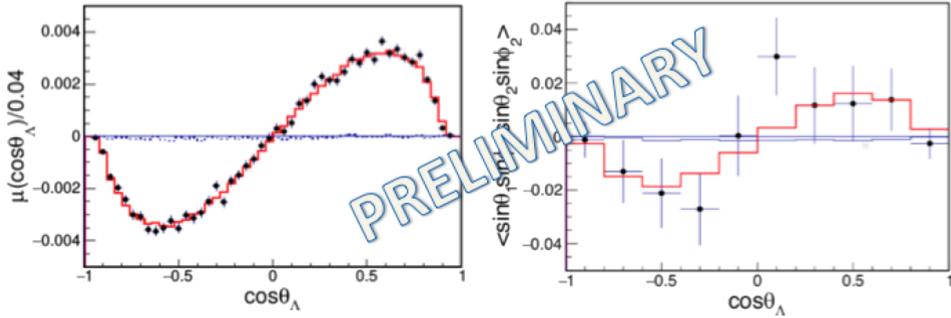
The asymmetry parameters  $\alpha_-$ ,  $\alpha_+$  and  $\bar{\alpha}_0$  have been determined using a simultaneous log-likelihood fit for the two decay processes (a)  $J/\psi \rightarrow \Lambda(\rightarrow p\pi^-)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$  and (b)  $J/\psi \rightarrow \Lambda(\rightarrow p\pi^-)\bar{\Lambda}(\rightarrow \bar{n}\pi^0)$  [17]. If  $\Delta\phi \neq 0$ ,  $\Lambda\bar{\Lambda}$  are produced polarized and it becomes possible to measure  $\alpha_-$ ,  $\alpha_+$  and  $\bar{\alpha}_0$  simultaneously. From approximately 420 k (a)- and 47 k (b)-events the relative phase is determined to be  $\Delta\phi = 42.4(6)_{\text{stat}}(5)_{\text{syst}}^\circ$ . The polarization can be illustrated by considering the moment  $\mu(\cos\theta_\Lambda) = (1/N_\Lambda) \cdot \sum_i^{N(\theta_\Lambda)} (\sin\theta_1^i \sin\phi_1^i - \sin\theta_2^i \sin\phi_2^i)$  as function of  $\cos\theta_\Lambda$  (left frame, fig. 1). For the other parameters our preliminary results (table 1) are more precise compared to all previous experiments and the preliminary value of  $\alpha_-$  is higher by 17(3)% compared to the current PDG estimate [3].  $A_{\text{CP}}$  has been measured with an improved precision compared to the current world average and is found to be consistent with 0.

**Table 1.** Preliminary BESIII results for the decay asymmetry parameters for  $J/\psi \rightarrow \Lambda\bar{\Lambda}$ .

Parameters	Preliminary results	Previous results
$\eta$	$0.461 \pm 0.006 \pm 0.007$	$0.469 \pm 0.027$ [13]
$\Delta\Phi(\text{rad})$	$0.740 \pm 0.010 \pm 0.008$	–
$\alpha_-$	$0.750 \pm 0.009 \pm 0.004$	$0.642 \pm 0.013$ [3]
$\alpha_+$	$-0.758 \pm 0.010 \pm 0.007$	$-0.71 \pm 0.08$ [3]
$\bar{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	–
$A_{\text{CP}}$	$-0.006 \pm 0.012 \pm 0.007$	$0.006 \pm 0.021$ [3]

### 3.2 $\Lambda\bar{\Lambda}$ EMFF measurement

To determine the values of  $R$  and  $\Delta\Phi$  the same log-likelihood fit is performed as for  $J/\psi \rightarrow \Lambda\bar{\Lambda}$  but due to the lower statistics  $\alpha_- = -\alpha_+$  have been fixed to  $\alpha_{-, \text{BESIII prel.}}$  and, as a cross-check, also to  $\alpha_{\text{PDG}}$ . For the first time we observe spin polarization of  $\Lambda\bar{\Lambda}$  for the time-like EMFF. The preliminary parameter values are  $R = 0.96(14)_{\text{stat}}(2)_{\text{syst}}$  ( $R = 0.94(16)_{\text{stat}}(3)_{\text{syst}}$ ) and  $\Delta\Phi = 37(12)_{\text{stat}}(6)_{\text{syst}}^\circ$  ( $\Delta\Phi = 42(16)_{\text{stat}}(8)_{\text{syst}}^\circ$ ) for the case that  $\alpha_- = -\alpha_+ = 0.750(0.642)$ . The polarization of  $\Lambda/\bar{\Lambda}$  is shown in the right frame of fig. 1. The preliminary values for the Born cross section is  $\sigma = 119.0(53)_{\text{stat}}(51)_{\text{syst}}$  pb. From the cross-section also the effective form factor  $|G|$  can be calculated,  $|G| = 0.123(3)_{\text{stat}}(3)_{\text{syst}}$ .



**Figure 1.** Moments  $\mu(\cos \theta_\Lambda)$  as function of  $\cos \theta_\Lambda$  for the process  $e^-e^+ \rightarrow J/\psi \rightarrow \Lambda(\rightarrow p\pi^-)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$  (left) and  $e^-e^+ \rightarrow \gamma^* \rightarrow \Lambda\bar{\Lambda}$  at  $\sqrt{s} = 2.396$  GeV (right).

## 4 Outlook

BESIII has collected the world's largest data sample in the energy region  $q^2 = 2.0\text{--}3.08$  GeV. This region covers several  $Y\bar{Y}$  states and EMFF results for many different hyperons can, therefore, be expected in the future. First preliminary results on  $J/\psi \rightarrow \Lambda\bar{\Lambda}$  have been presented but there are also many other weakly decaying hyperon-antihyperon states energetically accessible in  $J/\psi$  decays. Analyses are ongoing for  $J/\psi \rightarrow \Sigma\bar{\Sigma}$  and  $J/\psi \rightarrow \Xi\bar{\Xi}$ . In addition, BESIII is currently undertaking an experimental campaign to increase the available  $J/\psi$  statistics from 1.3 billion to 10 billion, which will allow for even more precise measurements.

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