Hyperon Structure and CP tests at BESIII

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Abstract. Hyperons are a powerful diagnostic tool that can shed light on some of the most intriguing questions in contemporary physics. Electromagnetic form factors (EMFFs) are currently the best way to study hyperon structure. In the time-like region the EMFFs can be complex with a relative phase. A non-zero phase polarizes the final state even when the initial state is unpolarized. A dedicated data sample collected by the BESIII experiment allowed for a first complete reconstruction of Λ in the time-like region. The ratio, $R = 0.96^{+0.14}_{-0.12}$ (stat)$^{+0.002}_{-0.003}$ (syst), and relative phase between the electric and magnetic form factor, $\Delta \Phi = 37^{+12}_{-6}$ (stat)$^{+2}_{-4}$ (syst), respectively. In addition, the BESIII experiment has collected the world’s largest $J/\psi$ data sample. Due to symmetric excellent detector conditions and low hadronic background, the experiment offers a clean environment for CP-violation tests using $J/\psi \rightarrow B\bar{B}$. That hyperons can be polarized allows for a simultaneous measurement of angular distributions of hyperons and antihyperons and to test CP symmetry directly. This has been done for the process $e^+e^- \rightarrow J/\psi \rightarrow \Lambda\bar{\Lambda}$ recently measured by the BESIII experiment. The experimental results showed that the asymmetry decay parameter $\alpha(\Lambda \rightarrow p\pi^-) = +0.750^{+0.009}_{-0.004}$, is nearly twenty percent larger compared to the old PDG tabulated value. The test on CP symmetry, $A_{CP,\Lambda\bar{\Lambda}} = -0.006^{+0.012}_{-0.007}$ is the most sensitive test for Λ CP-violation. Preliminary results are presented for the process $e^+e^- \rightarrow J/\psi \rightarrow \Sigma^+\Sigma^- \rightarrow p\pi^0\bar{p}\pi^0$. The asymmetry decay parameter $\alpha(\Sigma^- \rightarrow \bar{p}\pi^0) = +0.992^{+0.037}_{-0.008}$ and $A_{CP,\Sigma^+\Sigma^-} = -0.015 \pm 0.037 \pm 0.008$ are both measured for the first time.

1. Introduction
The fundamental objective of hadron physics is to understand the structure of matter at the femtometer scale. Despite much research on the proton and neutron there are still many questions which are unresolved, one example being the intrinsic structure of the nucleon [1]. To obtain information about the inner structure one uses the electromagnetic form factors (EMFFs) which provide information about the hadrons’ charge and magnetization density. The study of the electromagnetic structure has been important in understanding the internal structure of the nucleon [2, 3]. One of the ways to further our knowledge of the nucleon is to study the SU(3) baryon octet partners, the so called hyperons. Hyperons consist of one or more strange quarks and there exist relatively few form factors measurements. One can study both the space- and time-like region of hyperon EMFFs. The two regions can be related to each other via dispersion relations [4]. The space-like region is probed in scattering experiments of the type $e^- B \rightarrow e^- B$, where $B$ here denotes baryons in general and hyperons in particular. To access the space-like region requires either a hyperon beam or a target. Due to the hyperons’ short life span this is experimentally challenging to achieve. The time-like region is more straightforward as it can
be accessed in annihilation processes like $e^+e^- \rightarrow \gamma^* \rightarrow B\bar{B}$. To study hyperon EMFFs in the time-like region a dedicated data sample has been collected by the BESIII experiment [22]. The EMFFs are described with an electric and magnetic form factor, denoted $G_E$ and $G_M$, respectively. These are functions of the four-momentum squared, $q^2$. In the time-like region these can be complex, $G_E(q^2) = |G_E| \times e^{i\Phi_E}$ and $G_M(q^2) = |G_M| \times e^{i\Phi_M}$. There are four independent parameters to be determined: $|G_E|$, $|G_M|$, $\Phi_E$ and $\Phi_M$. The global complex phase cannot be observed, and, instead of two complex form factors, three real parameters are commonly used. These are an overall factor corresponding to the modulus of the hadronic magnetic form factor, $|G(q^2)|$, the modulus of the form factor ratio, $R$, and their relative phase $\Delta\Phi$. A non-zero phase between the form factors means that the pairs are produced with polarization. This can occur even if the colliding beams are unpolarized and in this case the polarization is perpendicular to the reaction plane and dependent on the hyperon scattering angle [6]. The polarization is experimentally accessible by studying angular distributions of hyperon two-body weak decays. The reason being that hyperons are self-analyzing, which means that the baryonic daughter particles are emitted according to the spin of the mother hyperon.

One of the unresolved questions of fundamental physics is why there exists a strong abundance of matter over anti-matter in the Universe. According to the current paradigm there existed an equal amount of antimatter at the Big Bang. The matter-antimatter asymmetry is therefore expected to have arisen via a physical mechanism, called baryogenesis [5]. Although the complete mechanism behind baryogenesis is unknown we know what criteria must be fulfilled. The three criteria, as stated by Sakharov, are that there must exist processes where: (i) baryon number (B) is violated; (ii) charge conjugation (C) and charge conjugation combined with parity (CP) are violated; (iii) the processes (i) and (ii) occur before thermal equilibrium. The CP symmetry allowed by the Standard Model is not sufficient to account for the observed discrepancy between matter and anti-matter. Thus, if an enhanced CP violation were to be measured this would indicate new physics and provide a clue to what happened to the missing anti-matter.

If hyperons are polarized, direct tests on CP symmetry can be conducted by simultaneously measuring the angular distributions of the hyperon and anti-hyperon decay products. Since any CP-violating effect is small, high precision is required. It is therefore a necessity that large data samples are available. Precise CP tests on hyperon-antihyperon pairs can be performed in the process $e^+e^- \rightarrow J/\psi \rightarrow B_1\bar{B}_2$ where the same formalism holds as in $e^+e^- \rightarrow \gamma^* \rightarrow B_1\bar{B}_2$. Here, the BESIII experiment has collected $10^{10}$ $J/\psi$. This is the world’s largest data sample produced directly from electron-positron annihilation, and allows for several stringent precision tests on CP symmetry.

2. Formalism
Consider the process $e^+e^- \rightarrow B_1\bar{B}_2$, (1)
where $B_1(\bar{B}_2)$ can be the $\Lambda(\bar{\Lambda})$ or $\Sigma^+(\Sigma^-)$ hyperons. If one assumes one-photon exchange, $e^+e^- \rightarrow \gamma^* \rightarrow B_1\bar{B}_2$, the Born cross section is given by

$$\sigma_{B_1\bar{B}_2}(q^2) = \frac{4\pi\alpha^2\beta}{3q^2} \left(|G_M(q^2)|^2 + \frac{1}{2\tau}|G_E(q^2)|^2\right),$$

(2)
where $\alpha$ is the fine-structure constant, $\beta = \sqrt{1 - 1/\tau}$ is the baryon velocity and $\tau = 4m_B^2/q^2$ ($m_B$ is the produced hyperon mass). For smaller data samples one can study the effective form factor, $|G(q^2)|$, which is a linear combination of the electric and magnetic form factors squared. A complete description of the EMFFs requires also the ratio between the electric and magnetic form factor, $R = |G_E/G_M|$, and the relative phase $\Delta\Phi = \Phi_E - \Phi_M$. Experimentally the ratio $R$ can be
accessed from the angular distribution parameter \( \eta = (\tau - R^2)(\tau + R^2) \). The determination of the parameters requires a multidimensional analysis which both takes into account the production and subsequent decays modes. In the developed formalism the production and decay process in Eq. 1 can be folded together [7]. The differential cross-section can be determined fully by five experimentally measured observables, \( \xi = (\theta, \theta_1, \phi_1, \theta_2, \phi_2) \). Here, \( \theta \) is the opening angle between the produced hyperon and the beam positron in the center-of-mass frame, while the other four angles are for the daughter proton and anti-proton in the helicity frame, see Figure 1. The helicity frame is obtained by boosting the proton(anti-proton) to the hyperon(anti-hyperon) rest frame. A right handed coordinate system defines the axes, where \( \hat{z} \) axis is in the direction of the hyperon momenta, \( p_{B_1} = - p_{B_2} \) and the \( \hat{y} \) axis is perpendicular to the reaction plane.

The differential cross section is given by \( d\sigma \propto W(\xi) d\xi \), where the full decomposition of \( W(\xi) \) is

\[
W(\xi) = T_0 + \eta T_5 + \alpha_1 \alpha_2 \left( T_1 + \sqrt{1 - \eta^2} \cos(\Delta \Phi) T_2 + \eta T_6 \right) + \sqrt{1 - \eta^2} \sin(\Delta \Phi) \left( \alpha_1 T_3 + \alpha_2 T_4 \right). \tag{3}
\]

The functions \( T_i \) depend only on the measured angles,

\[
\begin{align*}
T_0(\xi) &= 1, \\
T_1(\xi) &= \sin^2 \theta \sin \theta_1 \sin \theta_2 \cos \phi_1 \cos \phi_2 + \cos^2 \theta \cos \theta_1 \cos \theta_2, \\
T_2(\xi) &= \sin \theta \cos \theta \left( \sin \theta_1 \cos \theta_2 \cos \phi_1 + \cos \theta_1 \sin \theta_2 \cos \phi_2 \right), \\
T_3(\xi) &= \sin \theta \cos \theta \sin \theta_1 \sin \phi_1, \\
T_4(\xi) &= \sin \theta \cos \theta \sin \theta_2 \sin \phi_2, \\
T_5(\xi) &= \cos \theta, \\
T_6(\xi) &= \cos \theta_1 \cos \theta_2 - \sin \theta \sin \theta_1 \sin \theta_2 \sin \phi_1 \sin \phi_2. \tag{4}
\end{align*}
\]

Besides the angular distribution parameter \( \eta \) and \( \Delta \Phi \) the asymmetry decay parameters \( \alpha_1 \) and \( \alpha_2 \) are also part of the formalism. The parameter \( \alpha_1 \) here denotes the asymmetry decay parameters for the two decays \( \Lambda \rightarrow p\pi^- \) and \( \Sigma^+ \rightarrow p\pi^0 \), in the following denoted \( \alpha_- \) and \( \alpha_0 \); \( \alpha_2 \) represents the asymmetry decay parameters for \( \Lambda \rightarrow \bar{p}\pi^- \), \( \bar{\Lambda} \rightarrow \bar{n}\pi^0 \) and \( \Sigma^- \rightarrow \bar{p}\pi^0 \), denoted \( \bar{\alpha}_+ \), \( \bar{\alpha}_- \), and \( \bar{\alpha}_0 \), respectively. The asymmetry decay parameters are CP-odd and if CP-symmetry is

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**Figure 1.** The reaction system \( e^+e^- \) with the defined helicity angles.
conserved $\alpha_1 = -\alpha_2$. To test CP-symmetry $A_{CP} = (\alpha_1 + \alpha_2)/(\alpha_1 - \alpha_2)$ is measured and if CP is conserved, $A_{CP}$ is consistent with 0.

The Eq. 3 consists of four terms: the first two ($T_0 + \eta T_5$) describe the angular distribution of the hyperon, while the third and fourth term give the spin correlation and polarization, respectively. The polarization is in the $\hat{y}$-direction and is related to $\Delta \Phi$ via \[ P_y = \frac{\sqrt{1 - \eta^2 \sin \theta \cos \theta}}{1 + \eta \cos^2 \theta} \sin(\Delta \Phi). \] (5)

As can be seen, polarization only occurs when $\Delta \Phi \neq 0$. Also, it is only then that it becomes possible to determine $\alpha_1$ and $\alpha_2$ separately and test CP symmetry via $A_{CP}$.

For the form factor determinations the main objective is to measure $R$ and $\Delta \Phi$. The asymmetry decay parameters can be obtained more precisely from other processes where larger data samples are available, for example $J/\psi \rightarrow B_1 \bar{B}_2$. For form factor studies the third and fourth terms in Eq. 3 can be subjected to further simplification, by fixing $\alpha_1$ and assuming CP conservation $\alpha_1 = -\alpha_2$.

3. Previous experimental results

For the EMFF studies of $\Lambda$ there have been previous measurements conducted by the DM2 [8] and BaBar [9] collaborations. In 2018 the BESIII collaboration published cross section data points at four energies for $e^+ e^- \rightarrow \Lambda \bar{\Lambda}$ [10]. Of these four, the most noteworthy result is found at $q = 2.324$ GeV, 1 MeV above the $\Lambda \bar{\Lambda}$ production threshold. The cross section, $305 \pm 45^{\text{stat}} + 66^{\text{sys}}$ pb, is significantly larger than the theory prediction, where one rather expects a vanishing cross section. This enhancement requires further study, as it indicates a more involved physics scenario compared to what is previously assumed. The BaBar result provided a first measurement of the $\Lambda$ EMFFs [9]. Unfortunately, the data sample was not sufficient to determine $R$ with a high accuracy and no extraction of $\Delta \Phi$ was possible. There exists, however, a theoretical prediction of the $\Lambda$ polarization [11]. In that work the authors use various $\Lambda \bar{\Lambda}$ potential models with $p \bar{p} \rightarrow \Lambda \bar{\Lambda}$ experimental data from the PS185 experiment as constraining input [12].

Considering the decay $J/\psi \rightarrow \Lambda \bar{\Lambda}$ there are a few determinations of $\eta$ [13, 14, 15], but none of the relative phase, up until now. In addition, there has been no simultaneous determination of the asymmetry parameters $\alpha_-$ and $\alpha_+$. The situation for the $\Sigma^+$ hyperon is similar to $\Lambda$. The first measurement of $\eta$ of $J/\psi \rightarrow \Sigma^+ \Sigma^-$ was reported by the BES collaboration [16], while $n_{\psi(3686)}$ was studied with CLEO $\psi(3686) \rightarrow \Sigma^+ \Sigma^-$ data [17, 18, 19]. No measurement of $\Delta \Phi$ exist. The asymmetry decay parameter for $\Sigma^+ \rightarrow p\pi^0$ has been determined but not for $\Sigma^- \rightarrow \bar{p} \pi^0$ and subsequently no CP symmetry test has been conducted.

4. BESIII experiment

In these proceedings two recently published and one preliminary result from the BESIII collaboration are provided. The results come from data collected with the BESIII magnetic spectrometer [20] located at the Beijing Electron Positron Collider (BEPCII) [21] in Beijing, China. The form factors of $e^+ e^- \rightarrow \Lambda \bar{\Lambda}$ have been studied with a data sample corresponding to 66.9 pb$^{-1}$ collected at $q = 2.396$ GeV. The processes $J/\psi \rightarrow \Lambda \bar{\Lambda}$ and $J/\psi \rightarrow \Sigma^+ \Sigma^-$ have been analyzed from 1310.6 $\times 10^6$ $J/\psi$ decays. The pair $\Sigma^+ \Sigma^-$ has also been analyzed from the decay of the $\psi(3686)$ resonance. Those results are based on an available sample of 447.5 $\times 10^6$ $\psi(3686)$.
5. Results

5.1. $\Lambda\bar{\Lambda}$ EMFF measurement
The form factor measurement of $\Lambda$ is based on 555 events in the final event sample where $14 \pm 4$ of these are estimated to be background events [22]. The values of $R$ and $\Delta \Phi$ are obtained by performing a maximum log-likelihood fit to $W(\xi)$. The spin correlation and polarization terms in Eq. 3 are simplified by assuming CP conservation, $\alpha_- = -\bar{\alpha}_+$, and by fixing $\alpha_-$ to the value determined by BESIII from $J/\psi \rightarrow \Lambda \bar{\Lambda}$ (see below [22]). The value of $R = 0.96 \pm 0.14$ (stat) $\pm 0.002$ (syst) is determined with an unprecedented accuracy and, for the first time, the relative phase between $G_E$ and $G_M$ is determined, $\Delta \Phi = 37^\circ \pm 12^\circ$ (stat) $\pm 6^\circ$ (syst). The non-zero relative phase means that both $s$- and $d$-waves play a role in the production of the $\Lambda\bar{\Lambda}$ pair. Also, highly precise values of the cross section and effective form factor are obtained, $\sigma = 118.7 \pm 5.3$ (stat) $\pm 5.1$ (syst) pb and $|G| = 0.123 \pm 0.003$ (stat) $\pm 0.003$ (syst), respectively [22].

The first complete hyperon measurement allows for a better understanding of the $\Lambda\bar{\Lambda}$ interaction close to threshold. In the theory paper, reference [11], predictions were made based on final state interaction potentials. The precise determinations of $R$ and $\Delta \Phi$ from the BESIII collaboration now allows for ruling out some of the model predictions, as seen in Figure 5.1.

5.2. Asymmetry parameter measurement $J/\psi \rightarrow \Lambda\bar{\Lambda}$
To determine the asymmetry parameters $\alpha_-$, $\alpha_+$ and $\bar{\alpha}_n$ the two decay chains (i) $J/\psi \rightarrow \Lambda(\rightarrow p\pi^-)\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$ and (ii) $J/\psi \rightarrow \Lambda(\rightarrow p\pi^-)\bar{\Lambda}(\rightarrow \bar{n}\pi^0)$ were analyzed [23]. The final event samples consisted of approximately $4.2 \times 10^5$ type (i) and $4.7 \times 10^4$ type (ii) events. The decay parameters for type (i) and (ii) were determined simultaneously using the log-likelihood fit to the differential cross section $W(\xi)$ in Eq. 3. The relative phase is determined with high significance to be $\Delta \Phi = 42^\circ \pm 16^\circ$ (tot).

The results are shown in the left columns of Table 1. The value of $\alpha_-$ differs by more than five standard deviations from the old PDG value, $\alpha_-^{\text{PDG}} = 0.642 \pm 0.013$ (tot). This has the consequence that all $\Lambda$ polarization measurements relying on $\alpha_-^{\text{PDG}}$, must be either corrected...

![Figure 2](image-url)
Table 1. Final and preliminary results of $J/\psi \to \Lambda \bar{\Lambda}$ (two leftmost columns) and $\Psi \to \Sigma^+\Sigma^-$ (two rightmost columns), respectively. Second and third values are the statistical and systematical uncertainties, respectively.

| Param. $J/\psi \to \Lambda \bar{\Lambda}$ | Param. $\Psi \to \Sigma^+\Sigma^-$ |
|------------------------------------------|----------------------------------|
| $\eta_{J/\psi}$                         | $\eta_{J/\psi}$                  |
| $+0.461 \pm 0.006 \pm 0.007$            | $-0.507 \pm 0.006 \pm 0.002$     |
| $\Delta \Phi_{J/\psi}$                   | $\eta_{\Psi(3686)}$              |
| $42.4^\circ \pm 0.6^\circ \pm 0.5^\circ$| $+0.676 \pm 0.030 \pm 0.006$     |
| $\alpha_-$                               | $\Delta \Phi_{J/\psi}$           |
| $+0.750 \pm 0.009 \pm 0.004$            | $-15.4^\circ \pm 0.7^\circ \pm 0.3^\circ$ |
| $\bar{\alpha}_+$                         | $\Delta \Phi_{\Psi(3686)}$      |
| $-0.758 \pm 0.010 \pm 0.007$            | $+21.5^\circ \pm 4.0^\circ \pm 0.5^\circ$ |
| $\bar{\alpha}_i$                         | $\alpha_0$                       |
| $-0.692 \pm 0.016 \pm 0.006$            | $-0.999 \pm 0.037 \pm 0.010$     |
| $A_{CP,\Lambda \bar{\Lambda}}$          | $\bar{\alpha}_0$                |
| $-0.006 \pm 0.012 \pm 0.007$            | $+0.992 \pm 0.037 \pm 0.008$    |
| $A_{CP,\Sigma^+\Sigma^-}$               |                                  |
| $-0.015 \pm 0.037 \pm 0.008$            |                                  |

or re-measured. The test on CP symmetry, $A_{CP,\Lambda \bar{\Lambda}}$ is the most sensitive test on CP-violation for $\Lambda$ and is found to be consistent with the Standard Model expectation, $\sim O(10^{-5})$ [24].

5.3. Asymmetry parameter measurement $\Psi \to \Sigma^+\Sigma^-$

To better understand the role that the production mechanism has on the polarization of hyperons, it is important to determine it at several energies. This has been done for the first time for the $\Sigma$ hyperon as it has been studied at the two charmonium resonances $\Psi = J/\psi, \psi(3686)$. After all applied selection criteria the final event sample consists of $8.3 \times 10^4$ and $5.4 \times 10^3$ $J/\psi \to \Sigma^+\Sigma^-$ and $\psi(3686) \to \Sigma^+\Sigma^-$ events, respectively. All production and decay parameters are measured by performing a simultaneous log-likelihood fit to the data obtained at both resonances, see Table 1. The relative phase is determined for the first time in $J/\psi \to \Sigma^+\Sigma^-$ and $\psi(3686) \to \Sigma^+\Sigma^-$. For the latter resonance it is the first phase determination for any baryon. The asymmetry parameters of $\alpha_0$ and $\bar{\alpha}_0$ are also measured. The value determined by BESIII for $\alpha_0 = -0.999 \pm 0.037 \pm 0.010$ is in good agreement with the PDG average [25]. More importantly, $\bar{\alpha}_0$ is measured for the first time. As it is a simultaneous measurement of $\alpha_0$ and $\bar{\alpha}_0$ a test of CP symmetry is also conducted. $A_{CP,\Sigma^+\Sigma^-}$ is measured for the first time for any $\Sigma$ hyperon, $A_{CP,\Sigma^+\Sigma^-} = -0.015 \pm 0.037 \pm 0.008$. It is found to be consistent with CP conservation and hence also in agreement with the Standard Model prediction within uncertainties [24]. The polarization of $\Sigma^+$ at $J/\psi$ and $\psi(3686)$ can be seen from considering the moment $\mu(\cos \theta_{\Sigma^+}) = (m/N) \sum_k N_k (\sin \theta_1^k \cos \phi_1^k - \sin \theta_2^k \cos \phi_2^k)$, see Figure 3. Here $m$ equals the 20 bins in $\cos \theta_{\Sigma^+}$, $N$ is the total number of events in the data sample and $N_k$ is the number of events in the $k$-th $\cos \theta_{\Sigma^+}$ bin. The angles $\theta_1, \phi_1$ and $\theta_2, \phi_2$ denote the proton and anti-proton helicity angles, respectively. Had there been no polarization, one would have expected the experimental data points to follow the trend following phase space, indicated by the the blue dashed line in Figure 3.

6. Summary and Outlook

The first complete EMFF measurement of $\Lambda$ is a first step towards understanding hyperon structure. There are several energy scan points collected by the BESIII experiment where analyses are ongoing. Studies of hyperon-antihyperon pairs at the $J/\psi$ have allowed for precision tests of asymmetry decay parameters and CP symmetry.

In the future one can expect results for the other hyperons part of the SU(3) baryon octet. A particularly noteworthy hyperon to study at the $J/\psi$ resonance is the doubly weak decaying
Figure 3. Moments $\mu(\cos \theta)$ for $J/\psi \rightarrow \Sigma^+\Sigma^-$ (left) and $\psi(3686) \rightarrow \Sigma^+\Sigma^-$ (right) for non-acceptance corrected data as function of $\cos \theta$. The black points are experimental data; red solid line and blue dashed lines are simulated data with fit results and phase space, respectively.

particle $\Xi$ where phenomenological studies have revealed interesting aspects concerning its decay properties [26, 27]. In conclusion, one can expect interesting results related to hyperon production and decay properties from the BESIII collaboration in the forthcoming years.

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