HYPERON STRUCTURE AT BESIII*

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By dedicated off-resonance energy scans, the BESIII experiment provides unique information on the time-like structure of strange and single-charm hyperons. In particular, exploiting polarised and entangled hyperon–antihyperon pairs, has enabled the first complete measurement of the time-like structure of a baryon at a single energy. From this, we gain new insights into the strong interaction forming visible matter.

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1. Introduction

Nucleons constitute the major part of the visible mass of the Universe and are to this day the subject of intensive research. Recently, substantial progress has been made in our understanding of the *proton spin crisis* [1] and the *proton radius puzzle* [2]. New approaches now open up for corresponding advances on neutron that is more challenging to study due to its being both neutral and unstable. Calculations using lattice QCD reveal a negative charge radius [3], reflecting an asymmetric distribution of u- and d-quarks caused by the complex dynamics of the strong force. A deeper and more systematic understanding of this dynamics can be obtained by replacing one of the light quarks in the nucleon with a heavier strange or charm quark, *i.e.* transforming the nucleon into a hyperon. In these proceedings, we will discuss how hyperons can be used as a diagnostic tool to shed light on the forces from which the structure of visible matter emerges.

The main advantage of hyperons compared to nucleons is that their weak, parity-violating decay gives straightforward access to their spin properties. This is in contrast to protons which require dedicated polarimeter detectors for this purpose. In a hyperon decay, the emission angle of the daughter particles depends on the spin direction of the mother hyperon [4]. Hence,

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parameters with physical meaning, such as spin polarisation, can be retrieved from measurable quantities like decay angles. This feature makes hyperons a powerful diagnostic tool.

2. The BESIII experiment

The BEijing Spectrometer (BESIII) [5] at the Beijing Electron Positron Collider (BEPC-II) is perfectly suited to explore the structure of strange and single-charm hyperons. Hyperon–antihyperon pairs ($Y\bar{Y}$) for structure studies are primarily produced in one-photon exchange processes $e^+e^- \to \gamma^* \to Y\bar{Y}$ by off-resonance energy scans.

The BESIII detector covers 93% of the 4π solid angle. A small-cell, helium-based main drift chamber (MDC) surrounds the e^+e^- collision point and provides precise tracking of charged particles. The MDC is in turn surrounded by a time-of-flight system (TOF) of plastic scintillators, followed by an electromagnetic calorimeter (EMC) made of CsI(Tl) crystals. A superconducting solenoid magnet with a central field of 1.0 Tesla bends the trajectories of charged particles, thereby enabling momentum estimation. Finally, a muon counter (MUC) made of resistive plate chambers, is located outside the iron yoke of the solenoid.

3. Hyperon structure

The strong interaction dynamics between quarks in a composite system can be quantified by various structure functions. Among these, the electromagnetic form factors (EMFFs) have the advantage that they are experimentally accessible for nucleons as well as hyperons. *Space-like* EMFFs are probed in elastic electron–baryon ($e^-B \to e^-B$) scattering, and straightforward to access for the stable protons. The space-like electric G_{E} and magnetic G_{M} form factors are intuitive to understand since they are related to the charge- and magnetisation densities, respectively [6]. Neutrons provide a larger challenge since they are unstable when not bound in a nucleus, but recent calculations based on electron scattering data of *e.g.* deuterons reveal an intriguing charge distribution with the negative charge radius [3]. The next step is to study systems containing heavier quarks, such as hyperons. However, being even more unstable than neutrons, hyperons are unfeasible as a beam or target in scattering experiments. Hence, hyperons do not easily reveal their space-like structure but offer a window through *time-like* form factors [7]. These can be probed in $e^+e^- \to \gamma^* \to Y\bar{Y}$ reactions, provided the squared momentum transfer q^2 carried by γ^* is larger than $4M^2$. The intuitive space-like EMFFs and the experimentally accessible time-like dittos are related by dispersion relations [8].

Space-like EMFFs are real functions of q^2, in contrast to time-like ones which are complex. For spin 1/2 baryons, the electric and the magnetic form factors have a relative phase $\Delta\Phi$ [9] which reflects intermediate quantum fluctuations into *e.g.* $\pi\pi$. As $|q^2|$ approaches an asymptotic scale $q^2_{\rm asy}$, the time-like and the space-like EMFFs should converge to the same real value, resulting in a phase approaching an integer multiple of π [10]. From the asymptotic behaviour of the EMFF phase, space-like quantities such as the charge radius can be extracted [11]. But how do we measure this phase?

In the $e^+e^- \to Y\bar{Y}$ reaction, a non-zero phase manifests itself in a spin-polarised final state, even if the initial e^+e^- state is unpolarised [9]. The polarisation has a well-defined dependence on the hyperon scattering angle and depends on $\sin\Delta\Phi$ [12]. The polarisation is experimentally accessible through the angular distributions of the hyperon decay products.

4. Recent results from BESIII

The work presented here is based on a low-energy (2.0–3.08 GeV) scan from 2015 and a high-energy scan near the $\Lambda_c^+\bar{\Lambda}_c^-$ threshold carried out during 2014. The production and subsequent two-body decay of spin 1/2 hyperons in the $e^+e^- \to Y\bar{Y}(Y \to BM, \bar{Y} \to \bar{B}\bar{M})$ can be parameterised in terms of the phase $\Delta\Phi$, the form factor ratio $R = |G_{\rm E}/G_{\rm M}|$ and the decay parameters α_Y, and $\alpha_{\bar{Y}}$ [12, 13]. The process is fully described by five angles: the hyperon scattering angle as well as the polar and azimuthal decay angles of the proton (antiproton) from the hyperon (antihyperon) decay. This five-dimensional angular distribution has an unpolarised part, a spin-polarised part, and a spin-entangled part. The latter two typically require relatively large data samples containing several hundreds of hyperon–antihyperon pairs with a well-defined invariant mass. However, valuable information about the structure can be obtained from small data samples by studying the unpolarised part of the differential cross section.

4.1. Effective form-factor measurements

From the unpolarised cross section, the effective form factor can be extracted. This relies on the assumption that at energies that do not coincide with a vector charmonium resonance, one-photon exchange ($e^+e^- \to \gamma^* \to Y\bar{Y}$) dominates the hyperon–antihyperon production. In this case, the effective form factor $G_{\rm eff}$ can be calculated from the cross section [14].

Comparing the isosinglet hyperon Λ with the Σ isotriplet can reveal diquark correlations: Since the Σ^0 has isospin 1 and Λ isospin 0, and since the strange quark has no isospin, the difference lies in the *ud* diquark. Different isospin leads to different spin structure, which could explain the differences observed in Λ and Σ^0 effective form factors by the CLEO-c experiment [19].

Furthermore, the uu diquark in the Σ^+ should be in the same spin state as the ud diquark in Λ, resulting in similar effective form factors. The BESIII energy scan between 2.0 and 3.08 GeV indeed indicates such behaviour [15–17]. However, the Σ^+/Σ^- cross-section ratio disagrees by 10–30% with expectations from the SU(3) symmetry, which calls for a more complex model [16].

Above 3.0 GeV, vector charmonium resonances are abundantly produced in e^+e^- annihilations. The production of these states interferes with the electromagnetic process $e^+e^- \to Y\bar{Y}$ and the interpretation of the results in terms of EMFFs is not straightforward. In Refs. [19] from the CLEO-c experiment, it is argued that the contribution from vector charmonia such as $\Psi(3773)$ is negligible. However, a recent investigation by BESIII reveals a significant influence by the $\Psi(3773)$ in its vicinity [18]; at least an order of magnitude larger than assumed in Ref. [19].

Data at higher energies give access to structure functions of multi-strange and charm hyperons. The double-strange Ξ^- baryon has been studied with scan data between 2.90 GeV and 3.08 GeV. The results indicate the possible influence of a resonance around 3 GeV [20]. A dedicated scan near the $\Lambda_c^+\bar{\Lambda}_c^-$ threshold reveals a rapid rise of the cross section near threshold, which indicates a more complex underlying dynamics than the form-factor picture can encompass [21].

4.2. The ratio $R = |G_E/G_M|$

The $R = |G_{\mathrm{E}}/G_{\mathrm{M}}|$ ratio can be extracted from the hyperon scattering angle distribution, either by integrating out the decay angles [14] or by applying the multi-dimensional formalism from Ref. [12]. The former was done for the Σ^+ hyperon in Ref. [16] at 2.396 GeV and for the Λ_c^+ at 4.57 GeV and 4.60 GeV. The Λ form-factor ratio was studied with the full multi-dimensional formalism in Ref. [22] and at the energy corresponding to the $\Psi(3773)$ mass in Ref. [23]. However, the interpretation at the $\Psi(3773)$ resonance in terms of form factors is not straightforward, as concluded in Ref. [18]. The form-factor ratio measurements of the Λ and Λ_c^+ are consistent with unity, while that of the Σ^+ is significantly larger.

4.3. First phase measurement

The relatively large (66.9 pb^{-1}) off-resonance data sample at 2.396 GeV allows for a complete spin decomposition of the $e^+e^- \to \Lambda\bar{\Lambda}$ reaction. An exclusive event selection yields 555 $\Lambda\bar{\Lambda}$ candidates, on which the five-dimensional formalism of Ref. [12] is applied. This resulted in the first conclusive measurement of the form-factor phase $\Delta\Phi$. It was found to be $37^{\circ} \pm 12^{\circ} \pm 6^{\circ}$, where the first uncertainty is statistical and the second systematic. Together with the information on the effective form factor G_{eff} and the ratio R, these constitute the first "snapshot" of the time evolution of a $\Lambda\bar{\Lambda}$ pair [22]. The results have been used in a recent calculation of the Λ charge radius but more data are needed for an unambiguous solution [11]. Future measurements of the energy dependence of the electric and magnetic form factors can therefore be very illuminating.

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REFERENCES

[1] C.A. Aidala *et al.*, *Rev. Mod. Phys.* **85**, 655 (2013); C. Alexandrou *et al.*, *Phys. Rev. Lett.* **119**, 142002 (2017).

[2] H.-W. Hammer, U-G. Meißner, *Sci. Bull.* **65**, 257 (2020).

[3] H. Atac *et al.*, *Nat. Commun.* **12**, 1759 (2021).

[4] T.D. Lee, C.N. Yang, *Phys. Rev.* **108**, 1645 (1957).

[5] BESIII Collaboration, *Nucl. Instrum. Methods Phys. Res. A* **614**, 345 (2010).

[6] V. Punjabi *et al.*, *Eur. Phys. J. A* **51**, 79 (2015).

[7] S. Pacetti *et al.*, *Phys. Rep.* **550–551**, 1 (2015).

[8] M.A. Belushkin *et al.*, *Phys. Rev. -C* **75**, 035202 (2007).

[9] A.Z. Dubnickova *et al.*, *Nuovo Cim. A* **109**, 241 (1996).

[10] V.A. Matveev *et al.*, *Theor. Mat. Fiz.* **15**, 332 (1973); S. Brodsky *et al.*, *Phys. Rev. Lett.* **31**, 1153 (1973).

[11] A. Mangoni *et al.*, *Phys. Rev. D* **104**, 116016 (2021).

[12] G. Fäldt, A. Kupsc, *Phys. Lett. B* **772**, 16 (2017).

[13] G. Fäldt, *Eur. Phys. J. A* **52**, 141 (2016).

[14] BaBaR Collaboration, *Phys. Rev. D* **76**, 092006 (2007).

[15] BESIII Collaboration, *Phys. Rev. D* **97**, 032013 (2018).

[16] BESIII Collaboration, *Phys. Lett. B* **814**, 136110 (2021).

[17] BESIII Collaboration, *Phys. Lett. B* **831**, 137187 (2022).

[18] BESIII Collaboration, *Phys. Rev. D* **104**, L091104 (2021).

[19] S. Dobbs *et al.*, *Phys. Lett. B* **739**, 90 (2014); *Phys. Rev. D* **96**, 092004 (2017).

[20] BESIII Collaboration, *Phys. Rev. D* **103**, 012005 (2021).

[21] BESIII Collaboration, *Phys. Rev. Lett.* **120**, 132001 (2018).

[22] BESIII Collaboration, *Phys. Rev. Lett.* **123**, 122003 (2019).

[23] BESIII Collaboration, *Phys. Rev. D* **105**, L011101 (2022).