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J/ψ decays into baryon-antibaryon pairs

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Summary. — In 2019 the BESIII Collaboration collected a sample of 10 billions of J/ψ events and, using about 1.3×10^9 of them, observed baryon polarization in baryon-antibaryon decays, publishing a paper in *Nature Physics*. Using new data from both PDG and BESIII experiment and a model based on an effective strong Lagrangian, we separate, for the first time, the strong and electromagnetic contributions to the total branching ratio of the J/ψ decays into a pair of spin-1/2 baryon-antibaryon, finding a relative phase of $\varphi = (73 \pm 8)^\circ$.

1. – The BESIII experiment

The BESIII experiment operates at the e^+e^- Beijing Electron-Positron Collider II (BEPCII), located in Beijing, People's Republic of China at the Institute of High Energy Physics (IHEP). BEPCII is a double ring machine with a design luminosity of about $1 \cdot 10^{33}\,\text{cm}^{-2}\text{s}^{-1}$ and a center of mass (CM) energy in the range (2.0–4.6) GeV [1]. The scheme of the BESIII detector is shown in fig. 1 [2]. The physics program of the BESIII Collaboration includes tests of electroweak interactions, studies of light hadron spectroscopy and decay properties, studies of the production and decay properties of the main charmonia, studies of charm and τ-physics, search for glueballs, quark-hybrids, multi-quark states and other exotic states, precision measurements of QCD and CKM parameters and search for new physics. A discussion of the future plan of the Collaboration can be found in ref. [3]. In 2019 the BESIII detector finished accumulating a sample of 10 billions J/ψ, representing the world's largest data sample produced directly from e^+e^- annihilations.

2. – Entangled $\Lambda\overline{\Lambda}$ in J/ψ decays

Particles directly produced at e^+e^- colliders decay with relatively high probability into a baryon-antibaryon, $B\overline{B}$, pair [4]. In this kind of collider, electrons and positrons annihilate, producing a resonance, such as the J/ψ meson, that could decay into entangled $B\overline{B}$ pairs. For example in the case of $e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$, see fig. 2, the J/ψ,

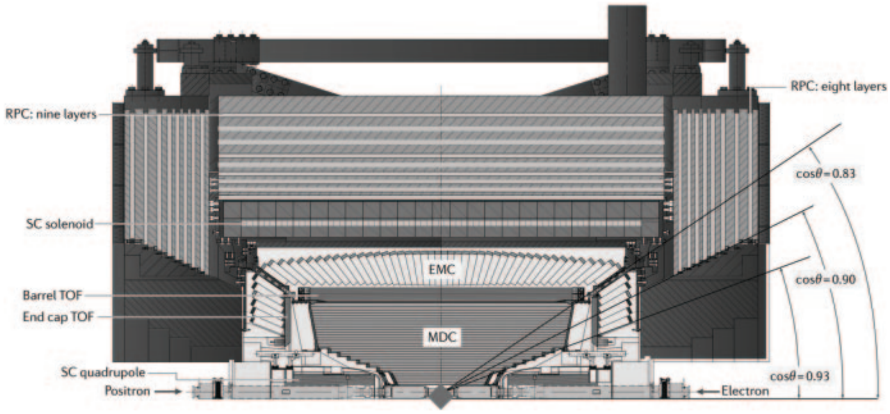

Fig. 1. – The BESIII detector [2].

produced at rest in a single photon annihilation process, subsequently decays into a $\Lambda\overline{\Lambda}$ pair [5].

2·1. *The process* $e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$. – The angular distribution and polarization of Λ and $\overline{\Lambda}$ is a function of the $J/\psi \to \Lambda\overline{\Lambda}$ parameter α_ψ of the angular distribution

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} \propto 1 + \alpha_\psi \cos^2\theta,$$

where θ is the angle between the outgoing baryon and the beam direction in the e^+e^- center-of-mass system, and the helicity phase $\Delta\phi$. Despite the fact that α_ψ is a well-known parameter [6], the helicity phase $\Delta\phi$ has never been measured before. Moreover, a non-vanishing $\Delta\phi$ is related to a Λ and $\overline{\Lambda}$ polarization along the normal to the scattering plane, $\hat{y}$ in fig. 3, and hence the polarization is a function of the angle θ_Λ.

The measurement of θ_Λ is performed by the study of the angular distribution of the decay products of Λ and $\overline{\Lambda}$, *i.e.*, $\Lambda \to p\pi^-$, $\overline{\Lambda} \to \overline{p}\pi^+$, $\overline{\Lambda} \to \overline{n}\pi^0$. Considering the $\Lambda \to p\pi^-$ decay the angular distribution of the daughter proton is given by [5]

$$\frac{1}{4\pi}(1 + \alpha_- \vec{P}_\Lambda \cdot \hat{n}),$$

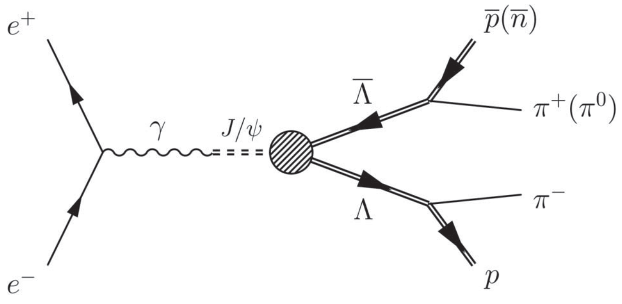

Fig. 2. – Feynman diagram for a typical process $e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$.

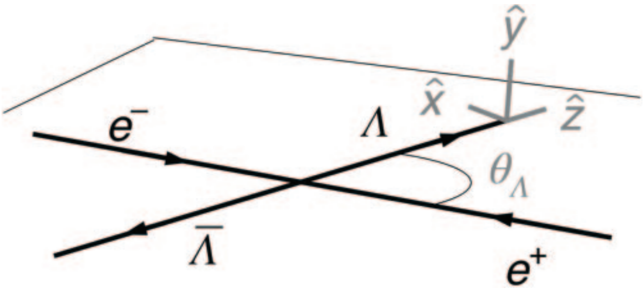

Fig. 3. – Illustration of the $e^+e^- \to J/\psi \to \Lambda\overline{\Lambda}$ process [5].

where $\vec{P}_\Lambda$ is the Λ polarization vector, $\hat{n}$ is the unit vector along the $\vec{p}$ momentum in the Λ rest frame and α_- is the asymmetry parameter that characterizes the degree of mixing of parity-conserving and parity-violating amplitudes in the process, with $-1 \le \alpha_- \le 1$. Analogously, the asymmetry parameters for the $\overline{\Lambda} \to \overline{p}\pi^+$ and $\overline{\Lambda} \to \overline{n}\pi^0$ decays are called, respectively, α_+ and $\overline{\alpha}_0$.

The joint angular distribution of the decay chain $J/\psi \to (\Lambda \to p\pi^-)(\overline{\Lambda} \to \overline{p}\pi^+)$ is a function of α_- and $\Delta\phi$ and is given by [7]

$$\begin{aligned}\mathcal{W}(\vec{\xi};\alpha_\psi,\Delta\phi,\alpha_-,\alpha_+) = {}& 1 + \alpha_\psi\cos^2\theta_\Lambda + \alpha_-\alpha_+[\sin^2\theta_\Lambda(n_{1,x}n_{2,x} - \alpha_\psi n_{1,y}n_{2,y})\\ &+ (\cos^2\theta_\Lambda + \alpha_\psi)n_{1,z}n_{2,z}] + \alpha_-\alpha_+\sqrt{1-\alpha_\psi^2}\cos(\Delta\phi)\sin\theta_\Lambda\\ &\cdot\cos\theta_\Lambda(n_{1,x}n_{2,z} + n_{1,z}n_{2,x}) + \sqrt{1-\alpha_\psi^2}\sin(\Delta\phi)\sin\theta_\Lambda\\ &\cdot\cos\theta_\Lambda(\alpha_- n_{1,y} + \alpha_+ n_{2,y}),\end{aligned}$$

where $\hat{n}_1$ ($\hat{n}_2$) is the unit vector in the direction of p ($\overline{p}$) in the rest frame of Λ ($\overline{\Lambda}$) and $\vec{\xi}$ is a set of kinematic variables $(\theta_\Lambda, \hat{n}_1, \hat{n}_2)$ which specifies the event configuration. In particular, the transverse polarization of the baryons is given by

$$P_y(\cos\theta_\Lambda) = P_y(\cos\theta_\Lambda) = \frac{\sqrt{1-\alpha_\psi^2}\sin(\Delta\phi)\cos\theta_\Lambda\sin\theta_\Lambda}{1+\alpha_\psi\cos^2\theta_\Lambda}.$$

The joint angular distribution allows an unambiguous determination of the parameter sets $(\alpha_\psi, \Delta_\phi, \alpha_-, \alpha_+)$ and $(\alpha_\psi, \Delta_\phi, \alpha_-, \overline{\alpha}_0)$.

2˙2. *Results.* – Using a sample of 1.31×10^9 J/ψ events, BESIII performed a high precision measurement of the parameter sets; the results are shown in table I, where the first uncertainty is statistical and the second is systematic [5]. The value of $\alpha_- = 0.750 \pm 0.009 \pm 0.004$ differs by more than 5 standard deviations from the world average value $\alpha_{\text{PDG}} = 0.642 \pm 0.013$, established in 1978 [9]. The actual PDG value has been updated and it takes into account the BESIII result [10].

Finally it is possible to calculate the CP asymmetry parameter A_{CP}

$$A_{\text{CP}} = \frac{\alpha_- + \alpha_+}{\alpha_- - \alpha_+} = -0.006 \pm 0.012 \pm 0.007,$$

Table I. – *Summary of the results.*

Parameter	New result	Previous result
α_ψ	$0.461 \pm 0.006 \pm 0.007$	0.469 ± 0.027 [6]
Δ_ϕ	$(42.4 \pm 0.6 \pm 0.5)^\circ$	–
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]
$\overline{\alpha}_0$	$-0.692 \pm 0.016 \pm 0.006$	–

that is compatible with the Standard Model (SM) prediction [11]

$$A_{\mathrm{CP}}^{\mathrm{StandardModel}} \simeq 10^{-4}.$$

3. – Decays of the J/ψ into baryon-antibaryon

The decays of the J/ψ meson into $B\overline{B}$ final states proceed via strong and electromagnetic (EM) interactions. It is possible to parametrize the total amplitude using three main contributions: a purely strong one (mediated by three gluons, ggg), a purely EM one (mediated by a single photon, γ) and a mixed strong-EM one (mediated by two gluons plus one photon, $gg\gamma$). It is important to include also the last term in the calculation, since it has been shown recently that it may not be negligible compared to the first two [12]. In particular the QCD calculation of the mixed strong-EM contribution is a very hard task due to the unknown hadronization process of gluons and photon into the final state. Moreover, this process does occur at a non-completely perturbative regime. We use the recent data from BESIII experiment and an effective strong Lagrangian model to separate, for the first time, the strong, the EM and the mixed strong-EM contributions to the total branching ratio (BR) of these J/ψ decays.

3·1. *Effective strong Lagrangian.* – We consider the decay of the J/ψ meson into pairs of spin 1/2 baryons of the $SU(3)$ octet. These baryons can be expressed using the octet matrix

$$B = \begin{pmatrix} \dfrac{\Lambda}{\sqrt{6}} + \dfrac{\Sigma^0}{\sqrt{2}} & \Sigma^+ & p \\ \Sigma^- & \dfrac{\Lambda}{\sqrt{6}} - \dfrac{\Sigma^0}{\sqrt{2}} & n \\ \Xi^- & \Xi^0 & -\dfrac{2\Lambda}{\sqrt{6}} \end{pmatrix}.$$

Since the J/ψ meson is an $SU(3)$ singlet state, the leading-order Lagrangian density is proportional to the invariant term $\mathrm{Tr}(B\overline{B})$ [13]. The effective strong Lagrangian can be built starting from this leading term and by taking into account the $SU(3)$ symmetry breaking due to EM and quark mass difference effects. The Lagrangian has the general form

$$\mathcal{L}_{\mathrm{eff}} = g\mathrm{Tr}(B\overline{B}) + d\mathrm{Tr}(\{B,\overline{B}\}S_e) + f\mathrm{Tr}([B,\overline{B}]S_e) + d'\mathrm{Tr}(\{B,\overline{B}\}S_m) + f'\mathrm{Tr}([B,\overline{B}]S_m)\,,$$

where the matrices S_m and S_e represent the $SU(3)$ symmetry breaking, respectively, due to mass ($m_u = m_d \neq m_s$) and EM effects and g, d, f, d', f' are constants. The full

Lagrangian can be written as a sum of single Lagrangians, one for each baryon pair on the final state, as follows:

$$\mathcal{L} = \mathcal{L}_{\Sigma^0\Lambda} + \mathcal{L}_p + \mathcal{L}_n + \mathcal{L}_{\Sigma^+} + \mathcal{L}_{\Sigma^-} + \mathcal{L}_{\Xi^0} + \mathcal{L}_{\Xi^-}\,. \tag{1}$$

3˙2. *Amplitudes parametrization.* – The Feynman amplitude for the decay of the J/ψ meson into a baryon-antibaryon pair can be written as the sum of three sub-amplitudes as [4]

$$\mathcal{A}_{J/\psi} = \mathcal{A}_{ggg} + \mathcal{A}_{gg\gamma} + \mathcal{A}_{\gamma},$$

where $\mathcal{A}_{ggg}$, $\mathcal{A}_{\gamma}$ and $\mathcal{A}_{gg\gamma}$ are the purely strong, purely EM and mixed strong-EM sub-amplitudes, respectively. By introducing the ratio R defined as

$$R \equiv \frac{\mathcal{A}_{gg\gamma}}{\mathcal{A}_{ggg}},$$

the amplitude becomes

$$\mathcal{A}_{J/\psi} = \mathcal{A}_{ggg}(1+R) + \mathcal{A}_{\gamma}. \tag{2}$$

The direct theoretical calculation of the ratio R is a hard task, as well as that of the sub-amplitude $\mathcal{A}_{gg\gamma}$. However the perturbative QCD (pQCD) prediction of the ratio R, for the charged final states [14], is

$$R_{\mathrm{pQCD}} \sim -\frac{4}{5}\frac{\alpha}{\alpha_S} \in \mathbb{R}, \tag{3}$$

but, at the J/ψ mass, the regime is not completely perturbative. Starting from eq. (1) and using eq. (2) we parametrize the total decay amplitude in terms of few parameters [15], as reported in table II. The five parameters G_0, D_e, D_m, F_e, F_m are real constants, φ is the relative phase between strong and EM amplitudes and R is the ratio of the mixed strong-EM amplitude to the strong one that we assume to be real [15].

Table II. – *Amplitudes parameterization.*

$B\overline{B}$	$\mathcal{A}_{B\overline{B}} = \mathcal{A}^{ggg}_{B\overline{B}} + \mathcal{A}^{gg\gamma}_{B\overline{B}} + \mathcal{A}^{\gamma}_{B\overline{B}}$
$\Sigma^0\overline{\Sigma}^0$	$(G_0+2D_m)e^{i\varphi}+D_e$
$\Lambda\overline{\Lambda}$	$(G_0-2D_m)e^{i\varphi}-D_e$
$\Lambda\overline{\Sigma}^0$+ c.c.	$\sqrt{3}\,D_e$
$p\overline{p}$	$(G_0-D_m+F_m)(1+R)e^{i\varphi}+D_e+F_e$
$n\overline{n}$	$(G_0-D_m+F_m)e^{i\varphi}-2\,D_e$
$\Sigma^+\overline{\Sigma}^-$	$(G_0+2D_m)(1+R)e^{i\varphi}+D_e+F_e$
$\Sigma^-\overline{\Sigma}^+$	$(G_0+2D_m)(1+R)e^{i\varphi}+D_e-F_e$
$\Xi^0\overline{\Xi}^0$	$(G_0-D_m-F_m)e^{i\varphi}-2\,D_e$
$\Xi^-\overline{\Xi}^+$	$(G_0-D_m-F_m)(1+R)e^{i\varphi}+D_e-F_e$

Table III. – *Branching ratios data from PDG* [8] *and BESIII experiment* [6] *(first two rows).*

Decay process	Branching ratio	Error
$J/\psi \to \Sigma^0\overline{\Sigma}^0$	$(1.164 \pm 0.023) \times 10^{-3}$	1.98%
$J/\psi \to \Lambda\overline{\Lambda}$	$(1.943 \pm 0.033) \times 10^{-3}$	1.70%
$J/\psi \to \Lambda\overline{\Sigma}^0 + \text{c.c.}$	$(2.83 \pm 0.23) \times 10^{-5}$	8.13%
$J/\psi \to p\overline{p}$	$(2.121 \pm 0.029) \times 10^{-3}$	1.37%
$J/\psi \to n\overline{n}$	$(2.09 \pm 0.16) \times 10^{-3}$	7.66%
$J/\psi \to \Sigma^+\overline{\Sigma}^-$	$(1.50 \pm 0.24) \times 10^{-3}$	16.00%
$J/\psi \to \Xi^0\overline{\Xi}^0$	$(1.17 \pm 0.04) \times 10^{-3}$	3.42%
$J/\psi \to \Xi^-\overline{\Xi}^+$	$(9.7 \pm 0.8) \times 10^{-4}$	8.25%

3·3. *Results.* – The seven real parameters G_0, D_e, D_m, F_e, F_m, φ and R are obtained minimizing the following χ^2:

$$\chi^2 = \sum_{k\in\{B\overline{B}\}} \left(\frac{\mathrm{BR}_k^{\mathrm{th}} - \mathrm{BR}_k^{\mathrm{exp}}}{\delta\mathrm{BR}_k^{\mathrm{exp}}}\right)^2 + \left(\frac{\mathrm{BR}_{p\overline{p}}^{\gamma,\mathrm{th}} - \mathrm{BR}_{p\overline{p}}^{\gamma,\mathrm{exp}}}{\delta\mathrm{BR}_{p\overline{p}}^{\gamma,\mathrm{exp}}}\right)^2,$$

where the sum runs over the eight baryon-antibaryon pairs for which experimental data are available. The data used as input are shown in table III, in addition to the EM $e^+e^- \to p\overline{p}$ cross section at the J/ψ mass given by

$$\sigma_{e^+e^-\to p\overline{p}}(M_{J/\psi}^2) = \frac{6912\,\pi\alpha^2(M_{J/\psi}^2+2M_p^2)}{M_{J/\psi}^{12}\,\mathrm{GeV}^{-8}} \times \left[\ln^2\left(\frac{M_{J/\psi}^2}{0.52^2\,\mathrm{GeV}^2}\right)+\pi^2\right]^{-2},$$

that has been obtained by the most recent measurement of the BESIII Collaboration [16]. The result from the fitting procedure is shown in table IV. In particular, we observe that at the J/ψ mass the regime is not completely perturbative, as mentioned before, by comparing our value for the ratio R with its pQCD prediction from eq. (3), *i.e.*,

$$|R| \sim 0.097 \neq |R_{\mathrm{pQCD}}| = \frac{4}{5}\frac{\alpha}{\alpha_S} \sim 0.030.$$

Table IV. – *Values of the parameters from the* χ^2 *minimization.*

G_0	$(5.73511 \pm 0.0059) \times 10^{-3}\,\mathrm{GeV}$
D_e	$(4.52 \pm 0.19) \times 10^{-4}\,\mathrm{GeV}$
D_m	$(-3.74 \pm 0.34) \times 10^{-4}\,\mathrm{GeV}$
F_e	$(7.91 \pm 0.62) \times 10^{-4}\,\mathrm{GeV}$
F_m	$(2.42 \pm 0.12) \times 10^{-4}\,\mathrm{GeV}$
φ	$1.27 \pm 0.14 = (73 \pm 8)^\circ$
R	$(-9.7 \pm 2.1) \times 10^{-2}$

TABLE V. – *Branching ratios from table III (second column), from parameters of table IV (third column) and their discrepancy.*

$B\overline{B}$	$\mathrm{BR}^{\mathrm{PDG}}_{B\overline{B}} \times 10^3$	$\mathrm{BR}_{B\overline{B}} \times 10^3$	Discrepancy (σ)
$\Sigma^0\overline{\Sigma}^0$	1.164 ± 0.023	1.160 ± 0.041	$\sim$0.09
$\Lambda\overline{\Lambda}$	1.943 ± 0.033	1.940 ± 0.055	$\sim$0.05
$\Lambda\overline{\Sigma}^0$+ c.c.	0.0283 ± 0.0023	0.0280 ± 0.0024	$\sim$0.09
$p\overline{p}$	2.121 ± 0.029	2.10 ± 0.16	$\sim$0.13
$n\overline{n}$	2.09 ± 0.16	2.10 ± 0.12	$\sim$0.05
$\Sigma^+\overline{\Sigma}^-$	1.50 ± 0.24	1.110 ± 0.086	$\sim$1.5
$\Sigma^-\overline{\Sigma}^+$	–	0.857 ± 0.051	–
$\Xi^0\overline{\Xi}^0$	1.17 ± 0.04	1.180 ± 0.072	$\sim$0.12
$\Xi^-\overline{\Xi}^+$	0.97 ± 0.08	0.979 ± 0.065	$\sim$0.09

Our value for the relative phase between strong and EM amplitudes, $\varphi = (73 \pm 8)^\circ$, is compatible with other independent results, such as $\varphi = (76 \pm 11)^\circ$, reported in ref. [17], and $\varphi = (89 \pm 8)^\circ$ for a nucleon-antinucleon final state [18]. This value is also compatible with the hypothesis of non-completely perturbative regime, since for $q^2 \to \infty$ all the amplitudes should become real. The BRs calculated using the obtained values for the parameters of table IV are shown in table V. It is interesting to notice that the value of $\mathrm{BR}(J/\psi \to \Sigma^-\overline{\Sigma}^+)$ represents a prediction of our model, since it has not been observed yet. Moreover, the predicted BR for the $J/\psi \to \Sigma^+\overline{\Sigma}^-$ decay is the only one that differs a lot from the corresponding experimental value.

4. – Conclusion

The BESIII Collaboration recently measured the polarization parameters and the helicity phase with high precision, using a huge sample of J/ψ events [5]. Moreover, the calculated CP asymmetry test parameter A_{CP} is compatible with the SM prediction $A^{\mathrm{SM}}_{\mathrm{CP}} \simeq 10^{-4}$.

Using the BESIII recent data on the J/ψ decays into baryon-antibaryon pairs and a strong effective Lagrangian model, the strong, the EM and the mixed strong-EM contributions to the total BR are separated for the first time [15]. Moreover, we calculated a relative phase between strong and EM amplitudes of $\varphi = (73 \pm 8)^\circ$ compatible with other works. This result and the obtained value for the ratio of the mixed strong-EM amplitude to the strong one, $|R| = 0.097 \neq |R_{\mathrm{pQCD}}| \sim 0.030$, confirm that at the J/ψ mass the regime is not completely perturbative. We made also a prediction for the unmeasured $\mathrm{BR}(J/\psi \to \Sigma^-\overline{\Sigma}^+)$. Finally, the obtained value for the branching ratio $\mathrm{BR}(J/\psi \to \Sigma^+\overline{\Sigma}^-)$ differs by 1.5 standard deviations from the corresponding PDG value, that has also the largest relative error.

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