Model-Independent Determination of the Spin of the $\Omega^-$ and Its Polarization

Alignment in $\psi(3686) \to \Omega^- \Omega^+$
(BESIII Collaboration)

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We present an analysis of the process $\psi(3686) \rightarrow \Omega^- \bar{\Omega}^+$ ($\Omega^- \rightarrow K^- \Lambda$, $\bar{\Omega}^+ \rightarrow K^+ \bar{\Lambda}$, $\Lambda \rightarrow p\pi^-$, $\bar{\Lambda} \rightarrow \bar{p}\pi^+$) based on a dataset of $448 \times 10^6 \psi(3686)$ decays collected with the BESIII detector at the BEPCII electron-positron collider. The helicity amplitudes for the process $\psi(3686) \rightarrow \Omega^- \bar{\Omega}^+$ and the decay parameters of the subsequent decay $\Omega^+ \rightarrow K^+ \Lambda$ ($\bar{\Omega}^+ \rightarrow K^+ \bar{\Lambda}$) are measured for the first time by a fit to the angular distribution of the complete decay chain, and the spin of the $\Omega^-$ is determined to be $3/2$ for the first time since its discovery more than 50 years ago.

DOI: 10.1103/PhysRevLett.126.092002

The discovery of the $\Omega^-$ [1] was a crucial step in our understanding of the microcosmos. It was a great triumph for the eightfold way model of baryons [2], and it led to the postulate of color charge [3]. A key feature of the eightfold way and the quark model is that the $\Omega^-$ spin is $J = 3/2$, a prediction that has never been unambiguously confirmed by experiment. The current best determination of $J = 3/2$ is based on an analysis [4] that assumes the spins of both the $\Xi_c^0$ and the $\Omega_c^0$ are their quark model values of $J = 1/2$.

One of the conceptually simplest processes in which a baryon-antibaryon pair can be created is electron-positron annihilation. In this letter, two $\Omega^-$ spin hypotheses, $J = 1/2$ or $J = 3/2$, are tested using the joint angular distribution of the sequential decays of the $e^+e^- \rightarrow \Omega^- \bar{\Omega}^+$ process. For the $J = 1/2$ hypothesis, two form factors are needed in the production of a baryon-antibaryon pair in electron-positron annihilation, and a clear vector polarization, strongly dependent on the baryon direction, is observed [5,6]. For the $J = 3/2$ hypothesis, the annihilation process involves four complex form factors [7]. In addition to vector polarization, the spin-3/2 fermions can have quadrupole and octupole polarization [8,9]. Polarization of the $\Omega^-$ can be studied using the chain of weak decays $\Omega^- \rightarrow K^- \Lambda$ and $\Lambda \rightarrow p\pi^-$, where the first decay is described by the ratio $\alpha_{\Omega^-}$ and the relative phase
between the parity-conserving $P$-wave and parity-violating $D$-wave ($S$-wave for the $J = 1/2$ hypothesis) decay amplitudes. The decay parameters cannot be calculated reliably in theory [10–12], and only $\alpha_{\Omega^\prime}$ has been previously measured [13–15].

The resonance production process $e^+e^- \to \psi(3686) \to \Omega^-\Omega^+$ was observed by the CLEO-c experiment with $27 \pm 5$ and $326 \pm 19$ events using the double-tag and single-tag technique as described in Refs. [16] and [17], respectively. With the world’s largest $\psi(3686)$ data sample of $(448.1 \pm 2.9) \times 10^6 \psi(3686)$ events accumulated in $e^+e^-$ annihilation with the BESIII detector [18], we are able to select about 4000 $\psi(3686) \to \Omega^-\Omega^+$ events, establish for the first time that the $\Omega^-$ spin is $J = 3/2$, and measure $\Omega^-$ polarizations in the $\psi(3686) \to \Omega^-\Omega^+$ reaction and evidence for the dominance of the parity-violating $D$-wave amplitude in the weak decay $\Omega^- \to K^-\Lambda$.

For the $J = 3/2$ hypothesis, in helicity formalism [19,20], there are four helicity amplitudes in the production density matrix for $e^+e^- \to \psi(3686) \to \Omega^-\Omega^+$ [21]. We define the ratios $A_{1(1/2),1(1/2)}A_{A_{1(1/2),1(1/2)}=1} = h_1 \epsilon^{\phi h}$, $A_{3(1/2),1(1/2)}A_{A_{3(1/2),1(1/2)}=1} = h_3 \epsilon^{\phi h}$, and $A_{3(1/2),3(1/2)}A_{A_{3(1/2),3(1/2)}=1} = h_4 \epsilon^{\phi h}$, where $h_1$ and $\phi_1 (i = 1, 3, 4)$ are real numbers to be determined from fits to data samples. The angular distribution is given by the trace of the $\Omega^-$ spin density matrix [21]: $1 + \alpha_{\psi(3686)} \cos^2 \theta_{\psi} - \alpha_\psi(3686) = [1 - 2(|h_1|^2 + |h_3|^2 + |h_4|^2)]/[1 + 2(|h_1|^2 + |h_3|^2 + |h_4|^2)]$. When considering the weak decays $\Omega^- \to K^-\Lambda$ and $\Lambda \to p\pi^-$, additional parameters $\alpha_{\Omega^-}$, $\alpha_\Lambda$, and $\phi_{\Omega^-}$: describing the ratio and relative phase between two helicity amplitudes are needed [21]. The joint angular distribution of $\theta_{\Omega^\prime}$, $\theta_{\Lambda}$, $\phi_{\Omega^\prime}$, $\theta_{p}$, and $\phi_{p}$ (see Fig. 1) is [21]

\[
\rho_{3/2} = \sum_{\mu=p,q} \sum_{\phi=0}^{-2} r_{\mu} b_{\mu} a_{\phi} a_{\phi}.
\]

For the $J = 1/2$ hypothesis, the joint angular distribution is defined as [21]

\[
\rho_{1/2} = \sum_{\mu=p,q} \sum_{\phi=0}^{-2} r_{\mu} a_{\mu} a_{\phi}.
\]

Here $r_{\mu}$, $b_{\mu}$, $a_{\mu}$, and $a_{\phi}$ are defined in terms of the helicity amplitudes [21]. By fitting the joint angular distribution of the selected events with Eqs. (1) and (2), we can, in principle, obtain the helicity amplitudes and $\Omega^-/\Lambda$ decay parameters.

To maximize the reconstruction efficiency, a single-tag method is implemented in which only the $\Omega^-$ or the $\Omega^+$ is reconstructed via $\Omega^- \to K^-\Lambda \to K^- p\pi^+$ or $\Omega^+ \to K^+\Lambda \to K^+ p\pi^+$, and the $\Omega^+$ or $\Omega^-$ on the recoil side is inferred from the missing mass of the reconstructed particles. The following event selections are described for $\Omega^- \to K^- p\pi^+$ as an example; the same selections are also applied for the $\Omega^+$ selection.

Charged tracks reconstructed from multilayer drift chamber (MDC) hits are required to be within a polar-angle ($\theta$) range of $|\cos \theta| < 0.93$. To determine the species of final-state particles, specific energy loss ($dE/dx$) information is used to form particle identification (PID) probabilities for pion, kaon, and proton hypotheses. Charged particles are identified in the hypothesis with the highest probability, and only one $K^-$ and one proton are required in each event. The rest of the negative charged tracks in an event are assumed to be $\pi^-$. To avoid potentially large differences between data and Monte Carlo (MC) simulation for very low momentum tracks, the transverse momenta of the $p$, $K^-$, and $\pi^-$ tracks are required to be larger than 0.2, 0.1, and 0.05 GeV/c, respectively.

The $\Lambda \to p\pi^-$ candidates are reconstructed by applying a vertex fit to the identified proton and a negatively charged pion with an invariant mass ($M_{p\pi^-}$) in the mass window of 1.110, 1.122 GeV/c². If more than one $\Lambda$ candidate is found, the one with $p\pi^-$ invariant mass closest to the nominal $\Lambda$ mass [22] is kept. The $\Lambda$ candidate is then combined with a $K^-$ track to reconstruct the $\Omega^-$. A secondary vertex fit is applied to $K^-\Lambda$ to improve the $\Omega^-$ mass-resolution and to suppress backgrounds. The invariant mass of $K^-\Lambda$ ($M_{K^-\Lambda}$) is a requirement in the mass window of 1.663, 1.681 GeV/c². To obtain the antibaryon candidates $\Omega^+$, we require the recoiling mass of $K^-\Lambda$ ($M_{K^-\Lambda}^{c.m.}$) in the mass window of 1.640, 1.692 GeV/c². All the mass windows are determined by optimizing the

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FIG. 1. Definition of the helicity angles used in the analysis. The helicity angles $\theta_{\Omega^\prime}$, $\theta_{\Lambda}$, $\phi_{\Omega^\prime}$, $\theta_{p}$, and $\phi_{p}$ are spherical coordinates of the $\Omega^-$, $\Lambda$, and $p$ momenta in three reference frames: the $e^+e^-$ c.m. system and the $\Omega^-$ and $\Lambda$ rest frames, respectively. The $\phi$ axis in the $e^+e^-$ c.m. system points along the incoming positron, and $z_{\Omega^\prime}$ is the $\Omega^-$ momentum direction. The polar axis direction in the $\Omega^-$ rest frame is $z_{\Omega^\prime}$, and $\hat{z}_{\Lambda}$ is along $\vec{z}_{\Omega^\prime} \times \hat{z}_{\Lambda}$. The $\Omega^-$ rest frame is $\hat{z}_{\Lambda}$, and $\hat{y}_{\Lambda}$ is along $\vec{z}_{\Omega^\prime} \times \hat{z}_{\Lambda}$. The $\Lambda$ rest frame is $\hat{z}_{\Lambda}$, and $\hat{y}_{\Lambda}$ is along $\vec{z}_{\Omega^\prime} \times \hat{z}_{\Lambda}$.
The continuum production of events is used to study the possible background sources. The pole collected at 3.65 GeV with an integrated luminosity of all the event selections, the red dashed lines show the signal components of the fit, and the blue dotted lines show the background components of the fit.

The distribution of $M_{K^−Λ}$ versus $M^\text{recoil}_{K^−}$ of the selected $K^−Λ$ candidates is shown in Fig. 2(a). A clear cluster of events in the data sample corresponding to $\psi(3686) \rightarrow Ω^−Ω^+$ is observed in the signal region of the red box area.

An inclusive $\psi(3686)$ MC sample with $4 \times 10^8 \psi(3686)$ events is used to study the possible background sources included in the simulation, and no peaking background is found. The continuum production of $Ω^−Ω^+$ is expected to be very low and neglected. This is also checked with data collected at 3.65 GeV with an integrated luminosity of 49 pb$^{-1}$ [about 7% of the $\psi(3686)$ data sample], and no significant $Ω^−Ω^+$ signal is observed.

Events in the signal region, shown in Fig. 2(a), are used to perform the angular distribution analysis. After applying all the event selections, 2507 $\psi(3686) \rightarrow Ω^−Ω^+$ candidates are selected by tagging the $Ω^−$ (called the $Ω^−$ sample) and 2238 candidates by tagging the $Ω^+$ (called the $Ω^+$ sample) by counting. The number of non-$Ω^-$ background events is estimated from the numbers of events in the $Ω^-$-mass sideband as $M^\text{recoil}_{K^−Λ} \in [1.644, 1.653]$ or $[1.692, 1.701]$ GeV/c$^2$. The $Ω^+$ ($Ω^+$) sample is estimated to contain $298 \pm 17$ (189 \pm 14) background events.

An unbinned maximum-likelihood fit to the selected events is performed to measure the free parameters in the angular distribution. The likelihood function is defined as

$$
\mathcal{L} = \Pi_{j=1}^{N_j} W(\zeta_j | H) = \Pi_{j=1}^{N_j} \frac{\rho(\zeta_j | H) \times e(\zeta_j)}{N(H)},
$$

where $j$ is the candidate event number, $\rho(\zeta_j | H)$ is the angular distribution function for the cascade decay in Eqs. (1) and (2), $\zeta = \{θ_Ω, θ_Λ, φ_Λ, θ_Ψ, φ_Ψ\}$ are the angular distribution variables, and $H$ contains the parameters to be determined from the fit. $N_j$ is the number of the selected events in the data samples. $N(H)$ is the normalization factor calculated with the MC integration method, and $e(\zeta_j)$ is the detection efficiency. Contributions from the background events to the likelihood have been considered by using events in the sideband regions of the $Ω^−$. The fit is performed by minimizing the objective function $S = –(ln L_{\text{data}} – ln L_{\text{bg}})$, where $L_{\text{data}}$ is the likelihood function of events selected in the signal region of $Ω^−$ and $Ω^+$ samples and $L_{\text{bg}}$ is the likelihood function of background events of these two single-tag samples estimated by the sideband method.

The decay parameters $α_Λ$ and $α_Ω$ are fixed to the Particle Data Group averages of previously measured values. Assuming that there is no $CP$ violation in $Ω^−$ and $Λ$ decays, $α_Λ = –α_3 = 0.753 \pm 0.007$ and $α_Ω = –α_Ω = 0.0154 \pm 0.0017$. A simultaneous fit is performed to the $Ω^−$ and $Ω^+$ events selected from data in which the constraint $φ_Ω = –φ_Ω$ is applied. The change of 2S of the fit assuming $J = 1/2$ and that of a linear combination of $J = 1/2$ and $J = 3/2$ is $–232$ with eight more free parameters, so we determine the significance of the $J = 3/2$ hypothesis over the $J = 1/2$ to be larger than $140\%$, and, thus, determine the spin of $Ω^-$ as $3/2$ unambiguously. For the fit with $J = 3/2$, we find two solutions with identical fit quality, as shown in Table I. Tests with large MC sample confirm the existence of two solutions in such fits, although its origin is not obvious in the expression of the decay amplitude. The statistical and systematic covariance matrices for the two solutions are supplied in Supplemental Material.

The signal MC events generated according to phase space distribution are weighted with matrix elements calculated with the parameters obtained from the fits, and the weighted MC sample predictions are compared with data in five distributions of the helicity angle, with the background contributions estimated from the $Ω^-$ sideband regions indicated as green histogram. We observe that the fit with $Ω^-$ spin $J = 3/2$ describes data very well, while $J = 1/2$ fails to describe data, as shown in Fig. 3(a) for $\cos \theta_Λ/Λ$, which has the most prominent difference. The moments $M_0$ and $M_8$ defined as $M_0 = 1/N \sum_{j=0}^{N} \sum_{k=0}^{3} b_{μ,κ} a_{κ,0}$ are

| Parameter | Solution I | Solution II |
|-----------|------------|-------------|
| $h_1$     | 0.30 ± 0.11 ± 0.04 | 0.31 ± 0.10 ± 0.04 |
| $φ_{h1}$  | 0.69 ± 0.11 ± 0.13 | 2.38 ± 0.37 ± 0.13 |
| $φ_{h2}$  | 0.26 ± 0.05 ± 0.02 | 0.27 ± 0.05 ± 0.01 |
| $φ_3$     | 2.60 ± 0.16 ± 0.08 | 2.57 ± 0.16 ± 0.04 |
| $φ_4$     | 0.51 ± 0.03 ± 0.01 | 0.51 ± 0.03 ± 0.01 |
| $φ_5$     | 0.34 ± 0.80 ± 0.31 | 1.37 ± 0.68 ± 0.16 |
| $φ_6$     | 4.29 ± 0.45 ± 0.23 | 4.15 ± 0.44 ± 0.16 |
compared between data and those two weighted MC samples, as shown in Figs. 3(b) and 3(c). Here \( N \) is the number of events in the data or MC samples. Clear preference of \( J = 3/2 \) over \( J = 1/2 \) is observed. Since the two sets of solutions describe the data equally well, we neglect all of the above contributions are added in quadrature to obtain the total systematic uncertainties as shown in Table II.

From Table I, we find that the magnitudes of the amplitudes are about the same in the two solutions, while the phases \( \phi_1 \) and \( \phi_4 \) can be very different. All the \( h_i \) values are less than one, which means that the amplitude \( A_{(1/2) - (1/2)} \) dominates the decay process. The value of \( \phi_{\Omega^-} \) provides information on whether the process is \( P \)-wave dominant (\( \phi_{\Omega^-} = 0 \)) or \( D \)-wave dominant (\( \phi_{\Omega^-} = \pi \)). By comparing the maximum-likelihood values between the fit with \( \phi_{\Omega^-} \) fixed to zero or \( \pi \) and the nominal fit, we find that the significance for non-zero \( \phi_{\Omega^-} \) is 3.7\( \sigma \), and that for a non-\( \pi \)\( \phi_{\Omega^-} \) is 1.5\( \sigma \). Thus, \( \phi_{\Omega^-} \) favors the \( D \)-wave-dominant case, which differs from the theoretical predictions of \( P \)-wave dominance [29]. The ratio of \( D \) to \( P \) wave can be calculated as \( |A_P|^2/|A_D|^2 = 2.4 \pm 0.2 \) (solution I) and \( |A_P|^2/|A_D|^2 = 3.3 \pm 2.9 \) (solution II), where the uncertainty is the sum in quadrature of the statistical and systematic uncertainties. Allowing \( a_{\Omega^-} \) to be determined by the fit, we obtain \( a_{\Omega^-} = -0.04 \pm 0.03 \), which does not contradict the quoted result from previous experiments but with poorer precision [13–15].

![Figure 3](image)

**FIG. 3.** (a) The cos \( \theta_{A/L} \) distributions of data (dots with error bars) and fits with \( J = 3/2 \) (red histogram) and \( J = 1/2 \) (blue histogram) hypotheses; (b) and (c) are the \( M_6 \) and \( M_8 \) distributions of data and fit results; and (d) distribution of the test statistic \( t = S_{J=1/2} - S_{J=3/2} \) for a series of MC simulations performed under the \( J = 1/2 \) (right peak) and \( J = 3/2 \) (left peak) hypotheses. The lines represent Gaussian fits to the simulated data points. The \( t \) value obtained from experimental data is indicated by the vertical bar.
In conclusion, based on $448 \times 10^6 \psi(3686)$ events, we observe $4035 \pm 76 \psi(3686) \rightarrow \Omega^{-}\bar{\Omega}^+$ signal events. We conduct the first study of the angular distribution of the three-stage decay and found that the hypothesis of $\Omega^{-}$ with a spin of 3/2 is preferred over a spin of 1/2 with a significance of more than 14 $\sigma$ and establishes the spin of the $\Omega^{-}$ to be 3/2 for the first time that is independent of any model-based assumptions. The helicity amplitudes of $\psi(3686) \rightarrow \Omega^{-}\bar{\Omega}^+$ and the decay parameter of $\Omega^{-} \rightarrow K^{-}\Lambda$, $\phi_{\Omega^{-}}$, are also measured for the first time. With the helicity amplitudes measured in Table I, $\alpha_{\psi(3686)} = 0.24 \pm 0.10$, where the uncertainty is the sum in quadrature of the statistical and systematic uncertainties.

With the helicity amplitudes measured in Table I, we calculate the $\cos \theta_{\Omega^{-}}$ dependence of the multipolar polarization operators as shown in Fig. 4. The uncertainties (statistical and systematic) are calculated using the covariance matrix of the fitted $h_i$ and $\phi_i$. For the process of $e^+e^- \rightarrow \psi(3686) \rightarrow \Omega^{-}\bar{\Omega}^+$, $\Omega^-$ particles not only have vector polarization ($r_1$), but also have quadrupole ($r_6, r_7, r_8$) and octupole ($r_{10}, r_{11}$) polarization contributions [8,9].

As a by-product, with the same data sample, the branching fraction for $\psi(3686) \rightarrow \Omega^{-}\bar{\Omega}^+$ is measured as $(5.85 \pm 0.12 \pm 0.25) \times 10^{-5}$, where the first uncertainty is statistical systematic and the second is systematic [25]. This result agrees with previous measurements [16,17] with improved precision.

The BESIII Collaboration thanks the staff of BEPCII and the IHEP computing center for their strong support. The authors thank Professor Zuotang Liang, Professor Yukun Song, Professor Xiaogang He, and Dr. Jusak Tandeant for useful discussions. This work is supported in part by National Key Basic Research Program of China under Contract No. 2020YFA0406300; National Natural Science Foundation of China (NSFC) under Contracts No. 11625523, No. 11635010, No. 11735014, No. 11822506, No. 11835012, No. 11935015, No. 11935016, No. 11935018, and No. 11961141012; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; Joint Large-Scale Scientific Facility Funds of the NSFC and CAS under Contracts No. U1732263 and No. U1832207; CAS Key Research Program of Frontier Sciences under Contracts No. QYZDJ-SSW-SLH003 and No. QYZDJ-SSW-SLH040; 100 Talents Program of CAS; Institute of Nuclear and Particle Physics (INPAC) and Shanghai Key Laboratory for Particle Physics and Cosmology; ERC under Contract No. 758462; German Research Foundation DFG under Contracts No. 443159800, Collaborative Research Center CRC 1044, FOR 2359, and GRK 214; Istituto Nazionale di Fisica Nucleare, Italy; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Science and Technology fund; Olle Engkvist Foundation under Contract No. 200-0605; STFC (United Kingdom); The Knut and Alice Wallenberg Foundation (Sweden) under Contract No. 2016.0157; The Royal Society, United Kingdom under Contracts No. DH140054 and No. DH160214; The Swedish Research Council; and U.S. Department of Energy under Contracts No. DE-FG02-05ER41374 and No. DE-SC-0012069.

FIG. 4. The $\cos \theta_{\Omega^{-}}$ dependence of the multipolar polarization operators. The solid lines represent the central values, and the shaded areas represent ± one standard deviation.
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[25] See Supplemental Material at http://link.aps.org/supplemental/10.1103/PhysRevLett.126.092002 for the statistical and systematic covariance matrices for the two solutions of the helicity amplitude fit, and for a brief description of the measurement of $\psi(3686) \rightarrow \Omega^- \Omega^+$ branching fraction, which includes Refs. [26,27].
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