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Measurement of the Spin of the Ω^- Hyperon at *BABAR*

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A measurement of the spin of the Ω^- hyperon produced through the exclusive process $\Xi_c^0 \to \Omega^- K^+$ is presented using a total integrated luminosity of 116 fb^{-1} recorded with the *BABAR* detector at the e^+e^- asymmetric-energy B-Factory at SLAC. Under the assumption that the Ξ_c^0 has spin 1/2, the angular distribution of the Λ from $\Omega^- \to \Lambda K^-$ decay is inconsistent with all half-integer

Ω^- spin values other than 3/2. Lower statistics data for the process $\Omega_c^0 \to \Omega^-\pi^+$ from a 230 fb^{-1} sample are also found to be consistent with Ω^- spin 3/2. If the Ξ_c^0 spin were 3/2, an Ω^- spin of 5/2 cannot be excluded.

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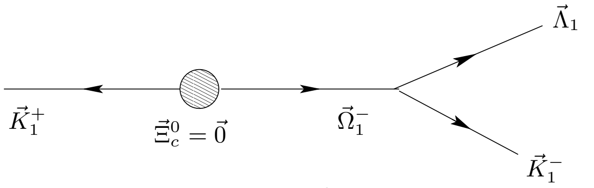
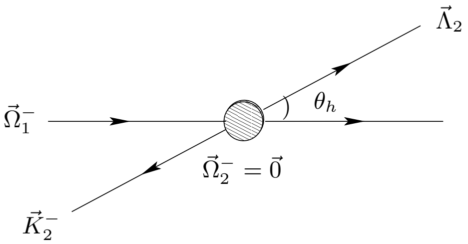


a) All decay products in the Ξ_c^0 rest-frame.



b) All decay products in the Ω^- rest-frame;
in this frame, $\vec{\Omega}_1^- \to \vec{\Omega}_2^- = \vec{0}$, $\vec{\Lambda}_1 \to \vec{\Lambda}_2$, $\vec{K}_1^- \to \vec{K}_2^-$.

FIG. 1: Schematic definition of the helicity angle θ_h in the decay chain $\Xi_c^0 \to \Omega^- K^+$, $\Omega^- \to \Lambda K^-$; as shown in b) θ_h is the angle between the Λ direction in the Ω^- rest-frame and the Ω^- direction in the Ξ_c^0 rest-frame (the quantization axis).

The $SU(3)$ classification scheme predicted [1] the existence of the Ω^- hyperon, an isosinglet with hypercharge $Y = -2$ and strangeness $S = -3$, as a member of the $J^P = 3/2^+$ ground state baryon decuplet. Such a particle was observed subsequently with the predicted mass in a bubble chamber experiment [2]. In previous attempts to confirm the spin of the Ω^- [3–5], $K^- \, p$ interactions in a liquid hydrogen bubble chamber were studied. In each case only a small Ω^- data sample was obtained, and the Ω^- production mechanism was not well understood. As a result, these experiments succeeded only in establishing that the Ω^- spin is greater than 1/2.

In this letter, measurements of the Ω^- spin are obtained using Ω^- samples [6] from the decay of Ξ_c^0 and Ω_c^0 charm baryons inclusively produced in e^+e^- collisions at center-of-mass energies 10.58 and 10.54 GeV. The primary Ω^- sample is obtained from the decay sequence $\Xi_c^0 \to \Omega^- K^+$, with $\Omega^- \to \Lambda K^-$, while a much smaller sample resulting from $\Omega_c^0 \to \Omega^-\pi^+$, with $\Omega^- \to \Lambda K^-$ is used for corroboration. It is assumed that each charm baryon type has spin 1/2 and, as a result of its inclusive production, that it is described by a diagonal spin projection density matrix. The analysis does not require that the diagonal matrix elements be equal.

The helicity formalism [7, 8] is applied in order to examine the implications of various Ω^- spin hypotheses for the angular distribution of the Λ from Ω^- decay. By choosing the quantization axis along the direction of the Ω^- in the charm baryon rest-frame, the Ω^- inherits the spin projection of the charm baryon, since any orbital angular momentum in the charm baryon decay has no projection in this direction. It follows that, regardless of the spin J of the Ω^-, the density matrix describing the Ω^- sample is diagonal, with non-zero values only for the $\pm 1/2$ spin projection elements, i.e. the helicity λ_i of the Ω^- can take only the values $\pm 1/2$. Since the final state Λ and K^- have spin values 1/2 and 0, respectively, the net final state helicity λ_f also can take only the values $\pm 1/2$. The helicity angle θ_h is then defined as the angle between the direction of the Λ in the rest-frame of the Ω^- and the quantization axis (Fig. 1).

The probability for the Λ to be produced with Euler angles $(\phi, \theta_h, 0)$ with respect to the quantization axis is given by the square of the amplitude ψ, characterizing the decay of an Ω^- with total angular momentum J and helicity λ_i to a 2-body system with net helicity λ_f,

$$\psi = A^J_{\lambda_f} D^{J*}_{\lambda_i \lambda_f}(\phi, \theta_h, 0), \tag{1}$$

where the transition matrix element $A^J_{\lambda_f}$ represents the coupling of the Ω^- to the final state, and $D^J_{\lambda_i\lambda_f}$ is an element of the Wigner rotation matrix [9]; $A^J_{\lambda_f}$ does not depend on λ_i because of rotational invariance (Wigner-Eckart theorem [10]). The angular distribution of the Λ is then given by the total intensity,

$$I \propto \sum_{\lambda_i, \lambda_f} \rho_i \left| A^J_{\lambda_f} D^{J*}_{\lambda_i \lambda_f}(\phi, \theta_h, 0) \right|^2, \tag{2}$$

where the ρ_i $(i = \pm 1/2)$ are the diagonal density matrix elements inherited from the charm baryon, and the sum is over all initial and final helicity states.

Using this expression, the Λ angular distribution integrated over ϕ is obtained for spin hypotheses $J_\Omega = 1/2$, 3/2, and 5/2, respectively as follows:

$$\begin{aligned}
dN/d\cos\theta_h &\propto 1 + \beta\cos\theta_h && (3)\\
dN/d\cos\theta_h &\propto 1 + 3\cos^2\theta_h + \beta\cos\theta_h(5 - 9\cos^2\theta_h) && (4)\\
dN/d\cos\theta_h &\propto 1 - 2\cos^2\theta_h + 5\cos^4\theta_h \\
&\qquad + \beta\cos\theta_{\rm h}(5 - 26\cos^2\theta_h + 25\cos^4\theta_h), && (5)
\end{aligned}$$

where the coefficient of the asymmetric term

$$\beta = \left[\frac{\rho_{1/2} - \rho_{-1/2}}{\rho_{1/2} + \rho_{-1/2}}\right] \left[\frac{\left|A^J_{1/2}\right|^2 - \left|A^J_{-1/2}\right|^2}{\left|A^J_{1/2}\right|^2 + \left|A^J_{-1/2}\right|^2}\right]$$

may be non-zero as a consequence of parity violation in charm baryon and Ω^- weak decay. Eqs. (3) and (4) are the distributions considered in connection with the discovery of the $\Delta(1232)$ resonance [11], generalized to account for parity violation.

The data samples used for this analysis were collected with the *BABAR* detector at the PEP-II asymmetric energy e^+e^- collider and correspond to a total integrated luminosity of 116 fb^{-1} and 230 fb^{-1} for the $\Xi_c^0 \to \Omega^- K^+$ and $\Omega_c^0 \to \Omega^- \pi^+$ samples, respectively. The detector is described in detail elsewhere [12]. The selection of Ξ_c^0 and Ω_c^0 candidates requires the intermediate reconstruction of events consistent with $\Omega^- \to \Lambda K^-$ and $\Lambda \to p\,\pi^-$. Particle identification selectors for the proton and the kaons, based on specific energy loss ($\mathrm{d}E/\mathrm{d}x$) and Cherenkov angle measurements, have been used [12]. Each intermediate state candidate is required to have its invariant mass within a $\pm 3\sigma$ mass window centered on the fitted peak position of the relevant distribution, where σ is the mass resolution obtained from the fit. In all cases, the fitted peak mass is consistent with the expected value [13]. The intermediate state invariant mass is then constrained to its nominal value [13].

Since the hyperons are long-lived, the signal-to-background ratio is improved by imposing vertex displacement criteria. The distance between the $\Omega^- K^+$ or $\Omega^-\pi^+$ vertex and the Ω^- decay vertex, when projected onto the plane perpendicular to the collision axis, must exceed 1.5 mm in the Ω^- direction. The distance between the Ω^- and Λ decay vertices is required to exceed 1.5 mm in the direction of the Λ momentum vector. In order to further enhance signal-to-background ratio, a selection criterion is imposed on the center-of-mass momentum p^* of the charm baryon: $p^* > 1.8$ GeV/c for Ξ_c^0 and $p^* > 2.5$ GeV/c for Ω_c^0 candidates. In addition, a minimum laboratory momentum requirement of 200 MeV/c is imposed on the π^+ daughter of the Ω_c^0 in order to reduce combinatorial background level due to soft pions. The invariant mass spectra of Ξ_c^0 and Ω_c^0 candidates in data are shown before efficiency correction in Figs. 2(a) and 2(b), respectively. The signal yields (770±33 Ξ_c^0 and 159±17 Ω_c^0 candidates) are obtained from fits with a double Gaussian (Ξ_c^0) or single Gaussian (Ω_c^0) signal function and a linear background function. The corresponding selection efficiencies obtained from Monte Carlo simulations are 14.7% and 15.8%, respectively.

For the Ω^- sample resulting from Ξ_c^0 decay, the uncorrected $\cos\theta_h(\Lambda)$ distribution is obtained by means of an unbinned maximum likelihood fit to the $\Omega^- K^+$ invariant mass spectrum corresponding to each of ten equal intervals of $\cos\theta_h(\Lambda)$ in the range -1 to 1. In each interval the Ξ_c^0 signal function shape is fixed to that obtained from the fit shown in Fig. 2 (a). The Ξ_c^0 reconstruction efficiency in each interval of $\cos\theta_h(\Lambda)$ is obtained from Monte Carlo simulation, and the resulting efficiency-corrected distribution is shown in Fig. 3. The measured efficiency varies linearly from 14.0% at $\cos\theta_h(\Lambda) = -1$ to 15.3% at $\cos\theta_h(\Lambda) = +1$, and so the shape of the angular distribution is changed only slightly by the correction procedure. The dashed curve corresponds to a fit of the $J_\Omega = 3/2$ parametrization of Eq. (4) and yields $\beta = 0.04 \pm 0.06$. The forward-backward asymmetry $A = (F-B)/(F+B)$ of the efficiency-corrected $\cos\theta_h(\Lambda)$ distribution of Fig. 3, where B (F) represents the number of signal events satisfying $\cos\theta_h(\Lambda) \leq 0$ (≥ 0), is $+0.001 \pm 0.019$. This and the fitted value of β indicate that the data show no significant asymmetry, and so we set $\beta = 0$ in subsequent fits. The solid curve represents the fit to the data with $\beta = 0$; the fit information relevant to Eq. (4) is indicated in Table 1.

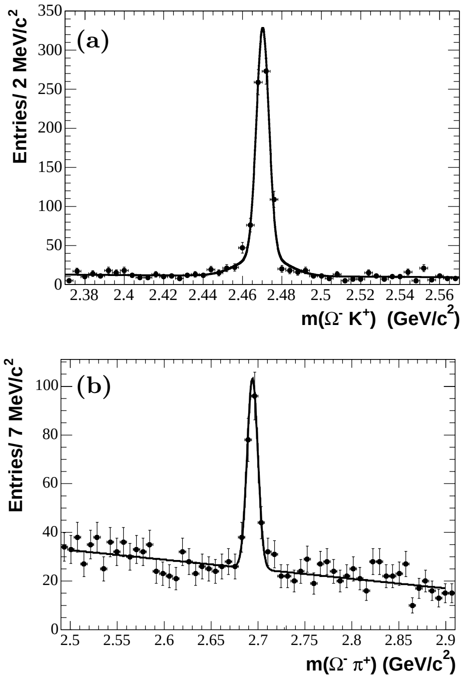


FIG. 2: The uncorrected $\Omega^- K^+$ (a) and $\Omega^-\pi^+$ (b) invariant mass spectra in data. The curves result from the fits described in the text.

The efficiency-corrected $\cos\theta_h(\Lambda)$ distribution with fits corresponding to Eqs. (3) and (5) with $\beta = 0$ is shown in Fig. 4. The solid line represents the expected distribution for $J_\Omega = 1/2$, while the dashed curve corresponds to $J_\Omega = 5/2$. The corresponding values of fit confidence level (C.L.) are extremely small (Table 1). For $J_\Omega \geq 7/2$, the predicted angular distribution increases even more steeply for $|\cos\theta_\mathrm{h}| \sim 1$ than for $J_\Omega = 5/2$ and exhibits $(2J_\Omega - 2)$ turning points. The relevant fit C.L.

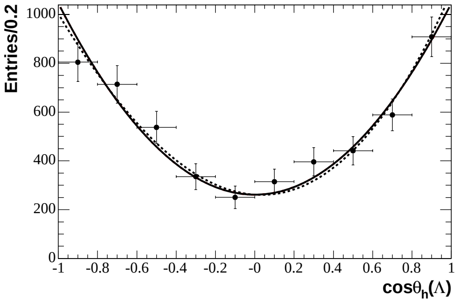


FIG. 3: The efficiency-corrected $\cos\theta_h(\Lambda)$ distribution for $\Xi_c^0 \to \Omega^- K^+$ data. The dashed curve shows the $J_\Omega = 3/2$ fit using Eq. (4), in which β allows for possible asymmetry. The solid curve represents the corresponding fit with $\beta = 0$.

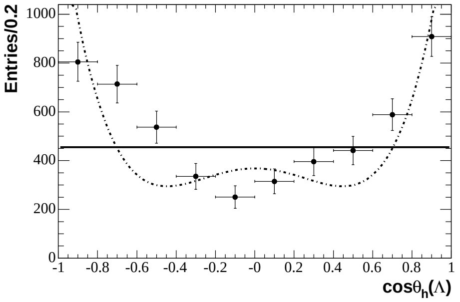


FIG. 4: The efficiency-corrected $\cos\theta_h(\Lambda)$ distribution for $\Xi_c^0 \to \Omega^- K^+$ data. The solid line represents the expected distribution for $J_\Omega = 1/2$, while the dashed curve corresponds to $J_\Omega = 5/2$. In each case, $\beta = 0$.

values are even smaller than that for $J_\Omega = 5/2$, and so $J_\Omega \geq 7/2$ can be excluded at C.L. greater than 99%.

These fit results were checked using the sample of Ω^- hyperons obtained from Ω_c baryon decays. The Ω_c baryon is presumed to belong to the **6** representation of an $SU(3)$ $J^P = 1/2^+$ multiplet [13], so that the Ω^- decay angular distribution should again be proportional to $(1 + 3\cos^2\theta_h)$. After efficiency-correction, the angular distribution shown in Fig. 5 is found to be consistent with $J_{\Omega^-} = 3/2$ with β again set to zero. The fit to the corrected distribution has $\chi^2/\mathrm{NDF} = 6.5/9$ and C.L. 0.69, and so is in very good agreement with the results obtained from Ξ_c^0 decay. The fit for β yields $\beta = 0.4 \pm 0.2$ and the value of the forward-backward asymmetry is $+0.013 \pm 0.058$.

J_Ω	Fit χ^2/NDF	Fit C.L.	Comment
1/2	100.4/9	1×10^{-17}	Fig. 4, solid line
3/2	6.5/9	0.69 ($\beta = 0$)	Fig. 3, solid curve
3/2	6.1/8	0.64 ($\beta \neq 0$)	Fig. 3, dashed curve
5/2	47.6/9	3×10^{-7}	Fig. 4, dashed curve

TABLE I: The $\cos\theta_h(\Lambda)$ angular distribution fit C.L. values corresponding to Ω^- spin hypotheses 1/2, 3/2 and 5/2 for $\Xi_c^0 \to \Omega^- K^+$ data assuming $J_{\Xi_c} = 1/2$.

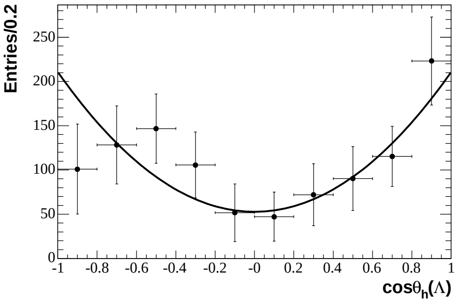


FIG. 5: The efficiency-corrected $\cos\theta_h(\Lambda)$ distribution in data for $\Omega_c^0 \to \Omega^- \pi^+$ events. The curve corresponds to $J_{\Omega_c} = 1/2$ and $J_{\Omega^-} = 3/2$ with $\beta = 0$.

The implications for the spin of the Ω^- if the spin of the Ξ_c^0 is assumed to be 3/2 are now considered. For $J_\Omega = 1/2$, the predicted decay angular distribution is again given by Eq. (3), and so this possibility can be ruled out.

If asymmetric contributions are ignored, the Ω^- angular distribution for spin values 3/2 and 5/2 are determined by the values of the quantities $x = \rho_{3/2} + \rho_{-3/2}$ and $(1 - x) = \rho_{1/2} + \rho_{-1/2}$. For $J_\Omega = 3/2$, $x = 0$ would yield a distribution given by Eq. (4) with $\beta = 0$, in excellent agreement with the data. However, for inclusive Ξ_c^0 production with the Ω^- direction in the Ξ_c^0 rest-frame as quantization axis, it would seem more reasonable to expect the spin projection states to be populated equally. This would yield $x = 0.5$, and would result in an isotropic Ω^- decay distribution, in clear disagreement with the observed behavior.

A consequence of such a Ξ_c^0 density matrix configuration would be that there should be no preferred direction in the decay to $\Omega^- K^+$ in the Ξ_c^0 rest-frame. This hypothesis has been tested in the present analysis by measuring the Ξ_c^0 polarization with respect to its production-plane normal; there is no evidence for such polarization. In addition, the spherical harmonic (Y_L^M) moments of the Ξ_c^0 decay angular distribution for $L \leq 6$ and $M \leq 6$ have been compared to those obtained from simulation in which the Ξ_c^0 decay is isotropic; no significant difference was found. It is therefore reasonable to infer that the combination $J_{\Xi_c} = 3/2$ and $J_\Omega = 3/2$ is disfavored.

For $J_\Omega = 5/2$ the situation is quite different. The decay angular distribution is then

$$\begin{aligned} dN/d\cos\theta_h \;&\propto\; 10\cos^4\theta_h - 4\cos^2\theta_h + 2 \\ &\quad -x(25\cos^4\theta_h - 18\cos^2\theta_h + 1). \end{aligned} \tag{6}$$

In this case, $x = 0.5$ gives

$$dN/d\cos\theta_h \propto -5\cos^4\theta_h + 10\cos^2\theta_h + 3, \tag{7}$$

which has a minimum at $\cos\theta_h = 0$, maxima at $\cos\theta_h = \pm 1$, and fits the observed angular distribution with C.L. 0.44. If x is allowed to vary, the best fit to the data has $x = 0.4$, which corresponds to

$$dN/d\cos\theta_h \propto 1 + 2\cos^2\theta_h\,; \tag{8}$$

the quartic term is thus cancelled, and fit C.L. 0.53 is obtained.

It follows from this discussion that for $J_{\Xi_c} = 3/2$, the hypothesis $J_\Omega = 1/2$ is ruled out, and $J_\Omega = 3/2$ may reasonably be considered disfavored; however, $J_\Omega = 5/2$ is entirely acceptable. For this reason, it has been emphasized that the determination that the Ω^- has spin 3/2 is entirely contingent upon the assumption that the spin of the Ξ_c^0 (and of the Ω_c^0) is 1/2.

In conclusion, the angular distributions of the decay products of the Ω^- baryon resulting from Ξ_c^0 and Ω_c^0 decays are well-described by a function $\propto (1 + 3\cos^2\theta_h)$. These observations are consistent with spin assignments 1/2 for the Ξ_c^0 and the Ω_c^0, and 3/2 for the Ω^-. Values of 1/2 and greater than 3/2 for the spin of the Ω^- yield C.L. values significantly less than 1% when spin 1/2 is assumed for the parent charm baryon.

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