

## Measurement of the Spin of the $\Omega^-$ Hyperon

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A measurement of the spin of the  $\Omega^-$  hyperon produced through the exclusive process  $\Xi_c^0 \rightarrow \Omega^- K^+$  is presented using a total integrated luminosity of  $116 \text{ fb}^{-1}$  recorded with the BABAR detector at the  $e^+e^-$

asymmetric-energy  $B$  factory at SLAC. Under the assumption that the  $\Xi_c^0$  has spin  $1/2$ , the angular distribution of the  $\Lambda$  from  $\Omega^- \rightarrow \Lambda K^-$  decay is inconsistent with all half-integer  $\Omega^-$  spin values other than  $3/2$ . Lower statistics data for the process  $\Omega_c^0 \rightarrow \Omega^- \pi^+$  from a  $230 \text{ fb}^{-1}$  sample are also found to be consistent with  $\Omega^-$  spin  $3/2$ . If the  $\Xi_c^0$  spin were  $3/2$ , an  $\Omega^-$  spin of  $5/2$  could not be excluded.

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The  $SU(3)$  classification scheme predicted [1] the existence of the  $\Omega^-$  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  $\Omega^-$  [3–5],  $K^- p$  interactions in a liquid hydrogen bubble chamber were studied. In each case only a small  $\Omega^-$  data sample was obtained, and the  $\Omega^-$  production mechanism was not well understood. As a result, these experiments succeeded only in establishing that the  $\Omega^-$  spin is greater than  $1/2$ .

In this Letter, measurements of the  $\Omega^-$  spin are obtained using  $\Omega^-$  samples [6] from the decay of  $\Xi_c^0$  and  $\Omega_c^0$  charm baryons inclusively produced in  $e^+e^-$  collisions at center-of-mass energies 10.58 and 10.54 GeV. The primary  $\Omega^-$  sample is obtained from the decay sequence  $\Xi_c^0 \rightarrow \Omega^- K^+$ , with  $\Omega^- \rightarrow \Lambda K^-$ , while a much smaller sample resulting from  $\Omega_c^0 \rightarrow \Omega^- \pi^+$ , with  $\Omega^- \rightarrow \Lambda K^-$ , 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  $\Omega^-$  spin hypotheses for the angular distribution of the  $\Lambda$  from  $\Omega^-$  decay. By choosing the quantization axis along the direction of the  $\Omega^-$  in the charm baryon rest frame, the  $\Omega^-$  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  $\Omega^-$ , the density matrix describing the  $\Omega^-$  sample is diagonal, with nonzero values only for the  $\pm 1/2$  spin projection elements; i.e., the helicity  $\lambda_i$  of the  $\Omega^-$  can take only the values  $\pm 1/2$ . Since the  $\Lambda$  and  $K^-$  in the final state have spin values  $1/2$  and  $0$ , respectively, the net final state helicity  $\lambda_f$  also can take only the values  $\pm 1/2$ . The helicity angle  $\theta_h$  is then defined as the angle between the direction of the  $\Lambda$  in the rest frame of the  $\Omega^-$  and the quantization axis (Fig. 1).

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

$$\psi = A_{\lambda_f}^J D_{\lambda_i \lambda_f}^{J*}(\phi, \theta_h, 0), \quad (1)$$

where the transition matrix element  $A_{\lambda_f}^J$  represents the coupling of the  $\Omega^-$  to the final state,  $D_{\lambda_i \lambda_f}^J$  is an element of the Wigner rotation matrix [9], and the  $*$  denotes complex conjugation;  $A_{\lambda_f}^J$  does not depend on  $\lambda_i$  because of rotational invariance (Wigner-Eckart theorem [10]). The angular distribution of the  $\Lambda$  is then given by the total intensity,

$$I \propto \sum_{\lambda_i, \lambda_f} \rho_{ii} |A_{\lambda_f}^J D_{\lambda_i \lambda_f}^{J*}(\phi, \theta_h, 0)|^2, \quad (2)$$

where the  $\rho_{ii}$  ( $i = \pm 1/2$ ) 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  $\Lambda$  angular distribution integrated over  $\phi$  is obtained for spin hypotheses  $J_\Omega = 1/2, 3/2$ , and  $5/2$ , respectively, as follows:

$$dN/d \cos \theta_h \propto 1 + \beta \cos \theta_h, \quad (3)$$

$$dN/d \cos \theta_h \propto 1 + 3 \cos^2 \theta_h + \beta \cos \theta_h (5 - 9 \cos^2 \theta_h), \quad (4)$$

$$dN/d \cos \theta_h \propto 1 - 2 \cos^2 \theta_h + 5 \cos^4 \theta_h + \beta \cos \theta_h (5 - 26 \cos^2 \theta_h + 25 \cos^4 \theta_h), \quad (5)$$

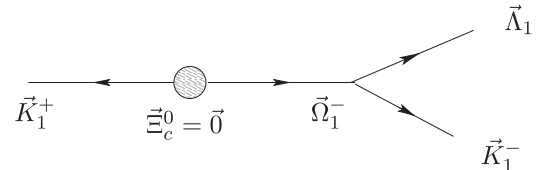
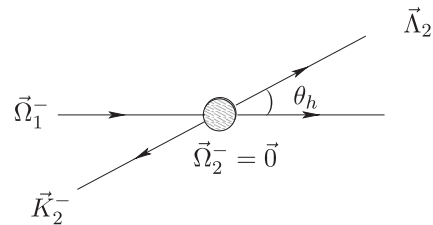
a) All decay products in the  $\Xi_c^0$  rest-frame.b) All decay products in the  $\Omega^-$  rest-frame; in this frame,  $\vec{\Omega}_1^- \rightarrow \vec{\Omega}_2^- = \vec{0}$ ,  $\vec{\Lambda}_1 \rightarrow \vec{\Lambda}_2$ ,  $\vec{K}_1^- \rightarrow \vec{K}_2^-$ .

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

where the coefficient of the asymmetric term

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

may be nonzero as a consequence of parity violation in charm baryon and  $\Omega^-$  weak decay. Equations (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 and 230  $\text{fb}^{-1}$  for the  $\Xi_c^0 \rightarrow \Omega^- K^+$  and  $\Omega_c^0 \rightarrow \Omega^- \pi^+$  samples, respectively. The detector is described in detail elsewhere [12]. The selection of  $\Xi_c^0$  and  $\Omega_c^0$  candidates requires the intermediate reconstruction of events consistent with  $\Omega^- \rightarrow \Lambda K^-$  and  $\Lambda \rightarrow p \pi^-$ . Particle identification selectors for the proton and the kaons, based on specific energy loss ( $dE/dx$ ) 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  $\sigma$  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  $\Omega^-$  decay vertex, when projected onto the plane perpendicular to the collision axis, must exceed 1.5 mm in the  $\Omega^-$  direction. The distance between the  $\Omega^-$  and  $\Lambda$  decay vertices is required to exceed 1.5 mm in the direction of the  $\Lambda$  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:  $p^* > 1.8 \text{ GeV}/c$  for  $\Xi_c^0$  and  $p^* > 2.5 \text{ GeV}/c$  for  $\Omega_c^0$  candidates. In addition, a minimum laboratory momentum requirement of 200  $\text{MeV}/c$  is imposed on the  $\pi^+$  daughter of the  $\Omega_c^0$  in order to reduce the combinatorial background level due to soft pions. The invariant mass spectra of  $\Xi_c^0$  and  $\Omega_c^0$  candidates in data are shown before efficiency correction in Figs. 2(a) and 2(b), respectively. The signal yields ( $770 \pm 33 \Xi_c^0$  and  $159 \pm 17 \Omega_c^0$  candidates) are obtained from fits with a double Gaussian ( $\Xi_c^0$ ) or single Gaussian ( $\Omega_c^0$ ) 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  $\Omega^-$  sample resulting from  $\Xi_c^0$  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  $\Xi_c^0$

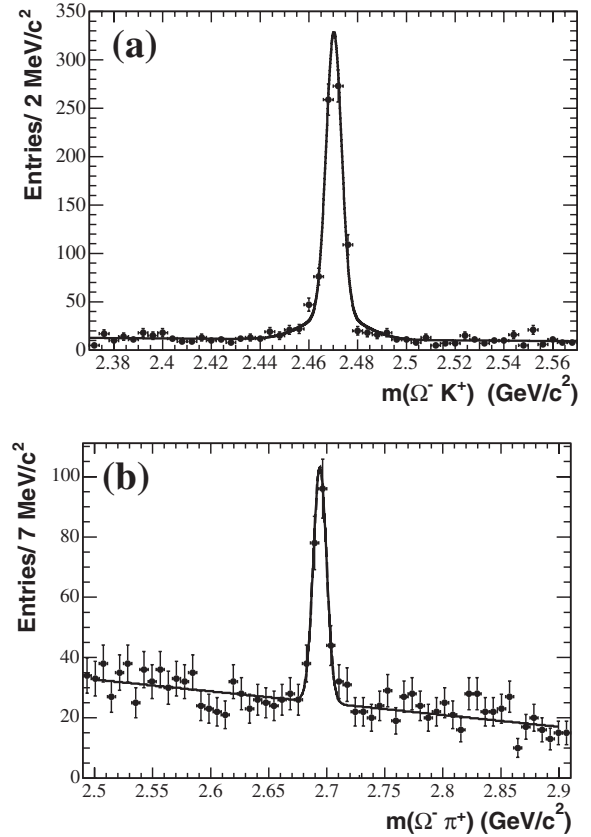


FIG. 2. The uncorrected  $\Omega^- K^+$  (a) and  $\Omega^- \pi^+$  (b) invariant mass spectra in data. The curves result from the fits described in the text.

signal function shape is fixed to that obtained from the fit shown in Fig. 2(a). The  $\Xi_c^0$  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  $\cos\theta_h(\Lambda) \leq 0$  ( $\geq 0$ ), is  $+0.001 \pm 0.019$ . This and the fitted value of  $\beta$  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 I.

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 dotted 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 I). For  $J_\Omega \geq 7/2$ , the

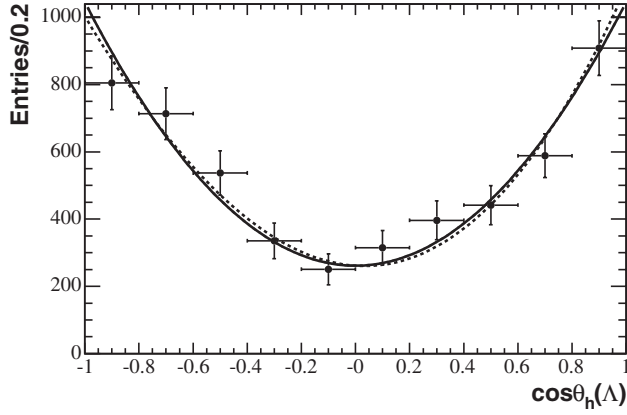


FIG. 3. The efficiency-corrected  $\cos\theta_h(\Lambda)$  distribution for  $\Xi_c^0 \rightarrow \Omega^- K^+$  data. The dashed curve shows the  $J_\Omega = 3/2$  fit using Eq. (4), in which  $\beta$  allows for possible asymmetry. The solid curve represents the corresponding fit with  $\beta = 0$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

predicted angular distribution increases even more steeply for  $|\cos\theta_h| \sim 1$  than for  $J_\Omega = 5/2$  and exhibits  $(2J_\Omega - 2)$  turning points. The relevant fit C.L. 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  $\Omega^-$  hyperons obtained from  $\Omega_c$  baryon decays. The  $\Omega_c$  baryon is presumed to belong to the **6** representation of an  $SU(3)$   $J^P = 1/2^+$  multiplet [13], so that the  $\Omega^-$  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  $\beta$  again set to zero. The fit to the corrected distribution has C.L. 0.69, and so is in very good agreement with the results obtained from  $\Xi_c^0$  decay. The fit for  $\beta$  yields  $\beta = 0.4 \pm 0.2$ , and the value of the forward-backward asymmetry is  $+0.013 \pm 0.058$ .

The implications for the spin of the  $\Omega^-$  if the spin of the  $\Xi_c^0$  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  $\Omega^-$  angular distribution for spin values  $3/2$  and  $5/2$  are determined by the values of the quantities  $x = \rho_{3/2\ 3/2} + \rho_{-3/2\ -3/2}$  and  $(1-x) = \rho_{1/2\ 1/2} + \rho_{-1/2\ -1/2}$ . For  $J_\Omega = 3/2$ ,  $x = 0$  would yield a distribution given by Eq. (4) with  $\beta = 0$ ,

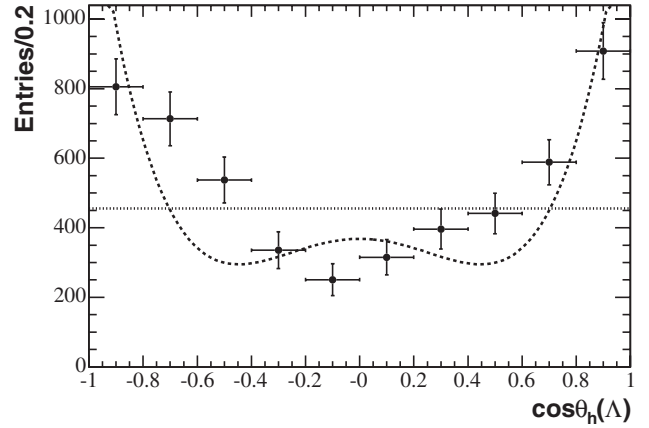


FIG. 4. The efficiency-corrected  $\cos\theta_h(\Lambda)$  distribution for  $\Xi_c^0 \rightarrow \Omega^- K^+$  data. The dotted line represents the expected distribution for  $J_\Omega = 1/2$ , while the dashed curve corresponds to  $J_\Omega = 5/2$ . In each case,  $\beta = 0$ .

in excellent agreement with the data. However, for inclusive  $\Xi_c^0$  production with the  $\Omega^-$  direction in the  $\Xi_c^0$  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  $\Omega^-$  decay distribution, in clear disagreement with the observed behavior.

A consequence of such a  $\Xi_c^0$  density matrix configuration would be that there should be no preferred direction in the decay to  $\Omega^- K^+$  in the  $\Xi_c^0$  rest frame. This hypothesis has been tested in the present analysis by measuring the  $\Xi_c^0$  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  $\Xi_c^0$  decay angular distribution for  $L \leq 6$  and  $M \leq 6$  have been compared to those obtained from simulation in which the  $\Xi_c^0$  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

$$dN/d\cos\theta_h \propto 10\cos^4\theta_h - 4\cos^2\theta_h + 2 - x(25\cos^4\theta_h - 18\cos^2\theta_h + 1). \quad (6)$$

TABLE I. The  $\cos\theta_h$  angular distribution fit C.L. values corresponding to the  $\Omega^-$  spin hypotheses  $1/2$ ,  $3/2$ , and  $5/2$  for  $\Xi_c^0 \rightarrow \Omega^- K^+$  data assuming  $J_{\Xi_c} = 1/2$ ; NDF denotes the number of degrees of freedom.

$J_\Omega$	Fit $\chi^2/\text{NDF}$	Fit C.L.	Comment
1/2	100.4/9	$1 \times 10^{-17}$	Figure 4, dotted line
3/2	6.5/9	0.69 ( $\beta = 0$ )	Figure 3, solid curve
3/2	6.1/8	0.64 ( $\beta \neq 0$ )	Figure 3, dashed curve
5/2	47.6/9	$3 \times 10^{-7}$	Figure 4, dashed curve

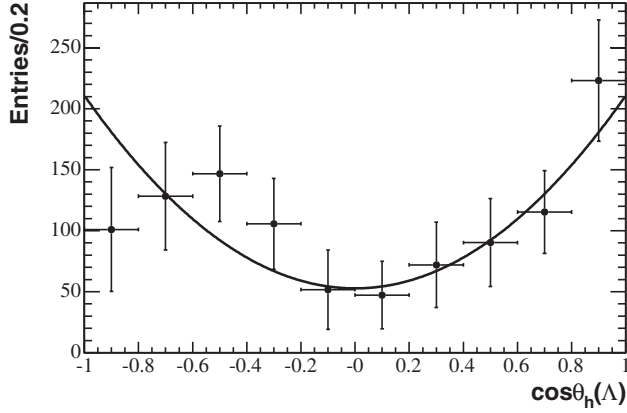


FIG. 5. The efficiency-corrected  $\cos\theta_h(\Lambda)$  distribution in data for  $\Omega_c^0 \rightarrow \Omega^- \pi^+$  events. The curve corresponds to  $J_{\Omega_c} = 1/2$  and  $J_{\Omega^-} = 3/2$  with  $\beta = 0$ .

In this case,  $x = 0.5$  gives

$$dN/d\cos\theta_h \propto -5\cos^4\theta_h + 10\cos^2\theta_h + 3, \quad (7)$$

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

$$dN/d\cos\theta_h \propto 1 + 2\cos^2\theta_h; \quad (8)$$

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  $\Omega^-$  has spin  $3/2$  is entirely contingent upon the assumption that the spin of the  $\Xi_c^0$  (and of the  $\Omega_c^0$ ) is  $1/2$ .

In conclusion, the angular distributions of the decay products of the  $\Omega^-$  baryon resulting from  $\Xi_c^0$  and  $\Omega_c^0$  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  $\Xi_c^0$  and the  $\Omega_c^0$ , and  $3/2$  for the  $\Omega^-$ . Values of  $1/2$  and greater than  $3/2$  for the spin of the  $\Omega^-$  yield C.L.

values significantly less than 1% when spin  $1/2$  is assumed for the parent charm baryon.

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