Measurement of the Spin of the $\Omega^-$ Hyperon at BABAR

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A measurement of the spin of the $\Omega^-$ hyperon produced through the exclusive process $\Xi_0^0 \rightarrow \Omega^- K^- e^+ e^-$ 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 $\Xi_0^0$ 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 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 cannot be excluded.

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The \( SU(3) \) classification scheme predicted \( \Xi_c^0 \) 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 \( \Xi_c \). In previous attempts to confirm the spin of the \( \Omega^- \) \( \Xi \), 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 \( \Xi_c^0 \) 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 inclusion, the angular momentum in the charm baryon decay has no 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 non-zero 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 final state \( \Lambda \) and \( K^- \) 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 \( \lambda_f \),

\[
\psi = A_{\lambda_f}^{\lambda_i} D_{\lambda_i, \lambda_f}^{J}(\phi, \theta_h, 0),
\]

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

\[
I \propto \sum_{\lambda_i, \lambda_f} \rho_i \left| A_{\lambda_f}^{\lambda_i} D_{\lambda_i, \lambda_f}^{J}(\phi, \theta_h, 0) \right|^2,
\]

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

\[
dN/d\cos\theta_h \propto 1 + \beta \cos\theta_h
\]
\[
dN/d\cos\theta_h \propto 1 + 3 \cos^2\theta_h + \beta \cos\theta_h(5 - 9 \cos^2\theta_h)
\]
\[
dN/d\cos\theta_h \propto 1 - 2 \cos^2\theta_h + 5 \cos^4\theta_h + \beta \cos\theta_h(5 - 26 \cos^2\theta_h + 25 \cos^4\theta_h)
\]
where the coefficient of the asymmetric term

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

may be non-zero as a consequence of parity violation in charm baryon and $\Omega^-$ 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 $\Xi^0_c \rightarrow \Omega^- K^+$ and $\Omega^0_c \rightarrow \Omega^- \pi^+$ samples, respectively. The detector is described in detail elsewhere [12]. The selection of $\Xi^0_c$ and $\Omega^0_c$ candidates requires the intermediate reconstruction of events consistent with $\Omega^- \rightarrow A K^- \Lambda$ 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 [12].

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: $p^* > 1.8$ GeV/c for $\Xi^0_c$ and $p^* > 2.5$ GeV/c for $\Omega^0_c$ candidates. In addition, a minimum laboratory momentum requirement of 200 MeV/c is imposed on the $\pi^+$ daughter of the $\Omega^0_c$ in order to reduce combinatorial background level due to soft pions. The invariant mass spectra of $\Xi^0_c$ and $\Omega^0_c$ candidates in data are shown before efficiency correction in Figs. 2(a) and 2(b), respectively. The signal yields (170$\pm33$ $\Xi^0_c$ and 159$\pm17$ $\Omega^0_c$ candidates) are obtained from fits with a double Gaussian ($\Xi^0_c$) or single Gaussian ($\Omega^0_c$) 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 $\Xi^0_c$ 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 $\Xi^0_c$ signal function shape is fixed to that obtained from the fit shown in Fig. 3(a). The $\Xi^0_c$ 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. 4. 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 $J_Q = 3/2$ 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 1.

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 $J_Q = 1/2$, while the dashed curve corresponds to $J_Q = 5/2$. The corresponding values of fit confidence level (C.L.) are extremely small (Table 1). For $J_Q \geq 7/2$, the predicted angular distribution increases even more steeply for $|\cos \theta_h| < 1$ than for $J_Q = 5/2$ and exhibits $(2J_Q - 2)$ turning points. The relevant fit C.L.
baryon is presumed to belong to the SU(3) multiplet with the distribution shown in Fig. 5 is found to be consistent with J_\Omega = 1/2, while the dashed curve corresponds to J_\Omega = 5/2. In each case, \beta = 0.

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, 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. 3 is found to be consistent with J_{\Omega^-} = 3/2 with \beta again set to zero. The fit to the corrected distribution has \chi^2/NDF = 6.5/9 and C.L. 0.69, and so is in very good agreement with the results obtained from \Xi^0_c 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^0_c 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 \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 \Xi^0_c production with the \Omega^- direction in the \Xi^0_c 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^0_c density matrix configuration would be that there should be no preferred direction in the decay to \Omega^- K^+ in the \Xi^0_c rest-frame. This hypothesis has been tested in the present analysis by measuring the \Xi^0_c polarization with respect to its production-plane normal; there is no evidence for such polarization. In addition, the spherical harmonic (Y^M_L) moments of the \Xi^0_c decay angular distribution for L \leq 6 and M \leq 6 have been compared to those obtained from simulation in which the \Xi^0_c decay is isotropic; no significant difference was found. It is therefore reasonable to infer that the combination J_{\Xi^0_c} = 3/2 and J_\Omega = 5/2 is disfavored. For J_\Omega = 5/2 the situation is quite different. The decay angular distribution is then

\frac{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). \hspace{1cm} (6)

In this case, x = 0.5 gives

\frac{dN}{d\cos \theta_h} \propto -5 \cos^3 \theta_h + 10 \cos^2 \theta_h + 3, \hspace{1cm} (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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[1] M. Gell-Mann, Proceedings of the International Conference on High-Energy Physics, p. 805 (1962).
[2] V. E. Barnes et al., Phys. Rev. Lett. 12, 204 (1964).
[3] M. Deutschmann et al., Phys. Lett. B73, 96 (1978).
[4] M. Baubillier et al., Phys. Lett. B378, 342 (1978).
[5] R. J. Hemingway, et al., Nucl. Phys. B142, 205 (1978).
[6] The use of charge conjugate states is implied throughout.
[7] M. Jacob and G. C. Wick, Annu. Phys. 7, 404 (1959).
[8] S. U. Chung, CERN Yellow Report, CERN 71-8 (1971).
[9] E. Wigner, Gruppentheorien, Friedr. Vieweg und Sohn, Braunschweig (1931); Group Theory, Academic Press, New York (1959).
[10] E. Wigner, Z. Phys. 43, 624 (1927); C. Eckart, Rev. Mod. Phys. 2, 305 (1930).
[11] H. L. Anderson, E. Fermi, E. A. Land and D. E. Nagle, Phys. Rev. 85, 936 (1952).
[12] B. Aubert et al. (BABAR), Nucl. Instr. Meth. A479, 1 (2002).
[13] S. Eidelman et al. (Particle Data Group), Phys. Lett. B592, 1 (2004).