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HADRON SPIN PHYSICS AT OPAL*

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Spin alignment of inclusive vector mesons and longitudinal polarization of Λ hyperons have been measured in a sample of 4.3 million hadronic Z^0 decays from the OPAL experiment at LEP. Leading, light vector mesons have been found to populate preferentially the helicity-zero state, a result which has no firm theoretical explanation. The values of off-diagonal elements of the helicity density matrix are in agreement with a theory based on the standard model with coherent fragmentation. The longitudinal polarization of the Λ is well described by a model in which the constituent strange quark carries all of the hyperon spin.

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1. Introduction

The primary quarks from Z^0 decay at LEP are highly polarized, with longitudinal polarizations of approximately -0.91 for down-type quarks and -0.64 for up-type quarks. It is an open question as to what part, if any, this polarization plays in determining the helicities of leading vector mesons in hadronic Z^0 decays. The vector mesons are $q\overline{q}$ systems of total spin one and orbital angular momentum zero, and any alignment of the meson spin must arise at least in part from the dynamics of the hadronization phase. In the case of leading hyperons, composed of a heavy quark and a light diquark, the picture is clearer, with the hyperon polarization expected directly to reflect any constituent heavy quark polarization. At LEP 1 the primary quark polarization is purely longitudinal; therefore any transverse polarization of final-state hyperons can only arise in the hadronization process and should be small.

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At OPAL, we have studied the vector-meson helicity density matrices for inclusively produced B^*, $D^*(2010)^{\pm}$, $\phi(1020)$ and $K^*(892)^0$ mesons, concentrating on large values of meson momentum fraction $x_p \equiv p_{\rm meson}/p_{\rm beam}$ (or energy fraction x_E), where the mesons have a high probability to contain a primary quark from Z^0 decay. We have measured the relative populations of the helicity $\lambda = 0$ and ± 1 states, as well as some off-diagonal elements of the helicity density matrix. For the K^{*0} meson we compare our results to a recent theory [1] based on a standard model description of the spin structure of the reaction $e^+e^- \to Z^0 \to q\overline{q}$, followed by coherent fragmentation of the $q\overline{q}$ pair. We have also studied the longitudinal and transverse polarization of Λ hyperons over a wide momentum range, and we compare the measurements with Monte Carlo models based on a simple constituent quark picture.

2. Decay formalisms

The formalism for the OPAL analyses of vector-meson helicity density matrices has been described fully in [2]. We work in the helicity-beam frame where the z-axis is the direction of the vector meson in the overall centre-of-mass system (the same as the laboratory at LEP), the y-axis is the vector product of this z-axis with the incident e^- beam direction, and the x-axis is such as to form a right-handed coordinate system. The angles $\theta_{\rm H}$ and $\phi_{\rm H}$ are the usual polar and azimuthal angles of a decay particle, measured in this frame. In the case of a vector meson decay to two pseudoscalars, the helicity density matrix elements ρ_{00} and ρ_{1-1} are determined by fitting the observed angular distributions W using:

$$W(\cos\theta_{\rm H}) = \frac{3}{4}\left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta_{\rm H}\right], \quad (1)$$

$$W(|\alpha|) = \frac{2}{\pi}\left[1 + 2\,{\rm Re}\,\rho_{1-1}\cos 2|\alpha|\,\right]. \quad (2)$$

The angle $\alpha = |\phi_{\rm H}| - \pi/2$ is introduced to exploit the symmetry properties of the distribution. The element ρ_{00} gives the relative intensity of mesons in the helicity-zero state, while the off-diagonal element ρ_{1-1} is a measure of coherence between the helicity $+1$ and helicity -1 states. For the case of no spin-alignment and no polarization, one has $\rho_{00} = 1/3$ and $\rho_{1-1} = 0$.

In the case of the weak Λ hyperon decay, $\Lambda \to p\pi$, parity violation results in a decay angular distribution in the Λ rest frame which has the form:

$$W(\cos\theta^*) \propto 1 + \alpha P_{\rm L}\cos\theta^*, \quad (3)$$

where $\cos\theta^*$ is the angle of the proton to the Λ flight direction measured in the CM frame, $\alpha = 0.642 \pm 0.013$ is the Λ decay parameter [3] and $P_{\rm L}$ is the longitudinal polarization of the Λ.

3. The OPAL detector and data samples

The OPAL detector is described in [4]. The spin analyses relied mainly on the central tracking chambers which consist of two layers of silicon microvertex detectors [5], a high-precision vertex drift chamber, a large-volume jet chamber, and a set of drift chambers which measure the coordinates of tracks along the direction of the beam. There is a homogeneous axial magnetic field of 0.435 T. Particle tracking is possible over the polar angle range $|\cos\theta| < 0.98$ for the full range of azimuthal angles. The impact parameter resolution of the microvertex detectors is about 20 μm both along and perpendicular to the beam direction. The tracking system gives a typical two-particle mass resolution of several MeV for light resonances, together with excellent V^0 reconstruction. The jet chamber can identify particle species from specific energy loss, dE/dx, with a resolution, $\sigma(dE/dx)/(dE/dx)$, of 3.5% for well-reconstructed, high-momentum tracks in multihadronic events [6].

The present analyses are based on a sample of some 4.3 million multihadronic Z^0 decays recorded at LEP 1 between 1990 and 1995. Reconstruction of inclusive charm and bottom particles relied to a large extent on the silicon microvertex detector, while identification of stable charged particles was done using the dE/dx capabilites of the jet chamber. The vector meson resonances were measured by fitting peaks in the appropriate inclusive mass spectra. Losses due to the acceptance and efficiency of the experiment and the data selection procedures were studied using large samples of Monte Carlo events, which had been generated using JETSET 7.4 [7] tuned to the OPAL data [8], and processed through a full simulation of the experiment [9] and the data reconstruction and analysis.

4. Vector meson helicity density matrix elements

We have measured helicity density matrix elements for four vector mesons, using the following decay modes (plus charge conjugates where appropriate):

- $B^* \to B\gamma$, with the low-energy photons converting to e^+e^- pairs in the central tracking system
- $D^*(2010)^+ \to D^0\pi^+$, followed by $D^0 \to K^-\pi^+$
- $\phi(1020) \to K^+K^-$
- $K^*(892)^0 \to K^\pm\pi^\mp$

Full details of the B^* meson study have been reported in [10]. The B meson candidates were reconstructed inclusively in jets containing a secondary vertex as described in [11], and the photons, which for kinematic reasons had laboratory momenta below 800 MeV$/c$, were well measured by their conversion in the material of the OPAL detector. The B^* signal was identified using the peak in the distribution of mass difference between the B^* and B candidate track combinations. We obtained a total of 1894 B^* meson candidates. From the angular distribution of the decay photons (not the same as equation (1) which applies only for vector decay to two pseudoscalars), we measured $\rho_{00} = 0.36 \pm 0.09$, clearly consistent with no spin alignment.

Details of our reconstruction of D^* candidates, and the selection cuts applied, are described in [12, 13]. For the spin analysis [2], D^0 candidates were required to lie in the mass range 1.79 to 1.94 GeV, and only those combinations with scaled energy $x_E > 0.2$ were used. The D^* signal was identified as the peak at around 145 MeV/c^2 in the spectrum of the mass difference between D^* and D^0 candidate track combinations. The density matrix elements were measured using a maximum likelihood fit to the decay angular distributions, with the element ρ_{00} evaluated separately in the fit for $c \to D^*$, $b \to D^*$ and background events. The charm component included both directly produced D^* mesons and those from excited charm hadron decays. The results for the charm component were: $\rho_{00} = 0.40 \pm 0.02$ and $\mathrm{Re}\,\rho_{1-1} = -0.039 \pm 0.014$. So the OPAL data show enhanced production of D^* in the state of zero helicity, and a small negative value of $\mathrm{Re}\,\rho_{1-1}$.

In the $\phi(1020)$ analysis [2], inclusive K^+K^- pairs with scaled momentum $x_p > 0.7$ were identified using the dE/dx measurements, and mass spectra were formed for three bins of the polar and azimuthal decay angles. Fits to these mass spectra to determine the $\phi(1020)$ intensities as functions of decay angles gave $\rho_{00} = 0.54 \pm 0.08$, again indicating preferential occupation of the helicity zero state. As in the case of the D^*, the off-diagonal element was found to have a small negative value, $\mathrm{Re}\,\rho_{1-1} = -0.11 \pm 0.07$, consistent with coherence in the primary $q\overline{q}$ fragmentation.

For the inclusive $K^*(892)^0$ analysis [14], which had much higher statistics than the other channels, it was possible to fit $K^\pm\pi^\mp$ mass spectra and measure the K^{*0} cross sections in six bins of decay angles for twelve ranges of x_p. The results, given in figure 1, show clear deviations from $\rho_{00}= 1/3$ and $\mathrm{Re}\,\rho_{1-1}= 0$ at large momentum where the K^* is most likely to contain a primary quark from the Z^0 decay.

Figure 2 summarizes our measurements of the matrix element ρ_{00} for the four vector mesons. Apart from the B^*, all leading vector mesons have $\rho_{00} > 1/3$, and there is some evidence that the deviation from equal population of the three helicity states is larger for the lighter vector mesons.

According to [1] the ratio $\mathrm{Re}\,\rho_{1-1}/(1 - \rho_{00})$ should be approximately equal to -0.10 for primary K^{*0} mesons measured in OPAL. This result is based on standard model parameters, coherent fragmentation and some plausible assumptions about hadronization, and takes account of the acceptance of the OPAL detector. Our measured value is -0.19 ± 0.05 for

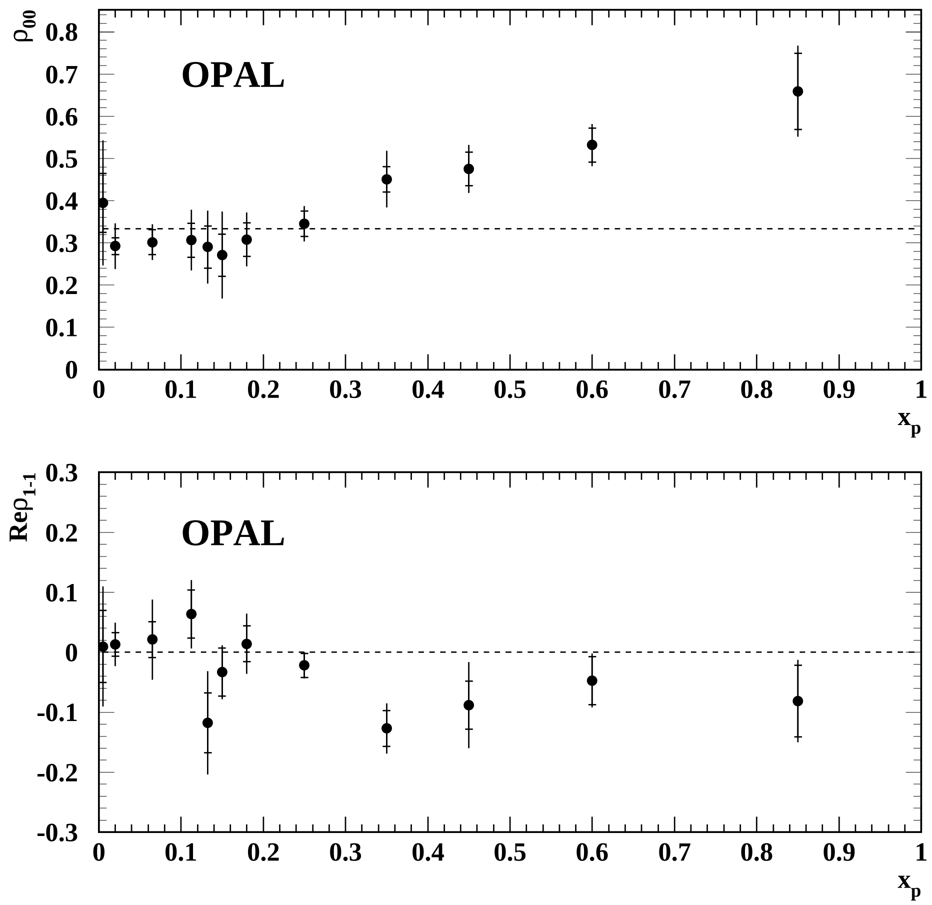

Fig. 1. Measured K^{*0} helicity density matrix elements, ρ_{00} and $\mathrm{Re}\,\rho_{1-1}$, as functions of x_p. The error bars are statistical and systematic combined in quadrature, with the tick marks giving the statistical errors only.

$x_p > 0.3$, in reasonable agreement with the prediction. We also measured $\mathrm{Re}\,\rho_{1-1}$ separately for two ranges of K^{*0} production angle relative to the electron beam: $|\cos\theta| < 0.5$ and $|\cos\theta| > 0.5$. The ratio of the results, 1.5 ± 0.7 over the range $x_p > 0.3$, is consistent within relatively large errors both with the predicted value [1] of 2.3 and with no variation of $\mathrm{Re}\,\rho_{1-1}$ with $\cos\theta$.

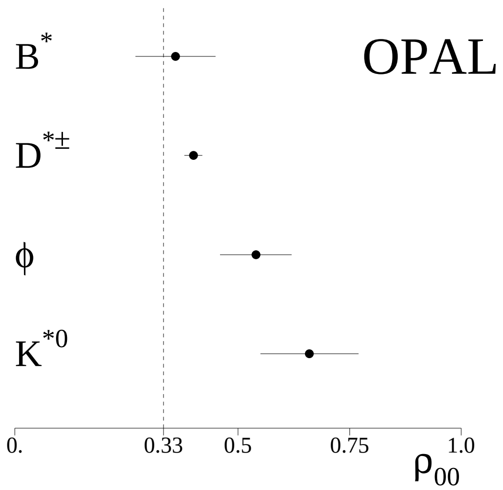

Fig. 2. Values of helicity density matrix element ρ_{00} for four vector mesons. The D^* result is for mesons produced by primary c quarks only. The results for ϕ and K^* are for leading particles with scaled momentum $x_p > 0.7$. A value of 1/3, shown by the dashed line, corresponds to no spin alignment.

5. Polarization of Λ hyperons

Figure 3 shows the OPAL measurements of the Λ longitudinal polarization obtained by fitting the observed decay distributions using equation (3) for nine ranges of scaled Λ energy x_E. The curves in figure 3 are from the JETSET Monte Carlo program with different models of baryon production as discussed below. For $x_E > 0.3$ the measured polarization is $-32.9 \pm 7.6\%$, in agreement with the value of $-32 \pm 7\%$ reported by ALEPH [15] over the same x_E range.

We have used the model of Gustafson and Häkkinen [16] to calculate the expected x_E dependence of the polarization using the JETSET Monte Carlo to determine the Λ production rates from each of several sources. In the model, the following assumptions were made:

- the spin of the Λ is determined by the spin of the s quark, so that a directly produced Λ will be polarized in the same way as the primary s quark;
- Λ particles which are decay products of heavier baryons containing the primary s quark will have a fraction of the polarization (estimates are included in the model for the Σ^0, Ξ^-, $\Sigma(1385)^\pm$, and $\Xi(1530)$);
- if a primary u or d quark becomes a constituent of a Λ, it forms part of a spin-0 ud diquark pair and its polarization is lost;
- Λ particles containing only quarks produced in the fragmentation are not polarized.

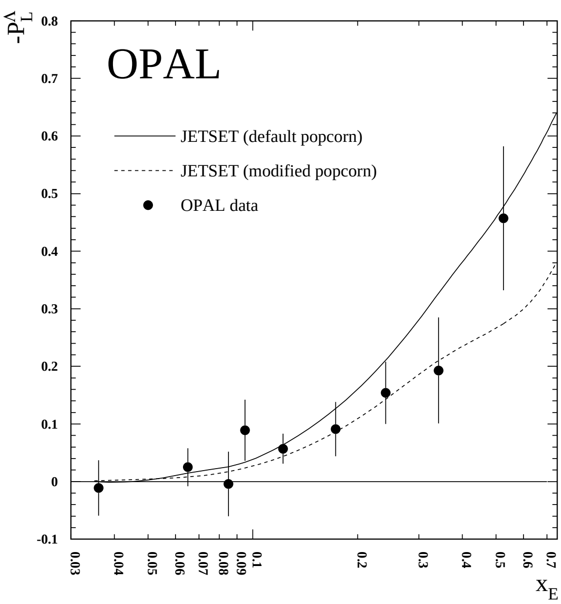

Fig. 3. The measured longitudinal polarization of Λ hyperons as a function of scaled Λ energy x_E. The curves show the prediction of models discussed in the text.

We used two versions of JETSET7.4: the default version of the "popcorn" model of baryon production [17], tuned by OPAL (see [18]); and the recent "modified popcorn scheme" [19], also with the OPAL tuning and some other adjustments [20]. As seen in figure 3, both versions give good agreement with the measurements. Although this relatively simple constituent quark model fits the observations, there are other possible interpretations of the Λ polarization, as discussed in [21].

We also measured the transverse polarization, $P_{\rm T}$, of Λ baryons using the direction defined by the cross product of the Λ momentum and the event thrust axis. For transverse momenta $p_{\rm T} > 0.3$ GeV$/c$, we measure $P_{\rm T}^{\Lambda} = 0.9 \pm 0.9\%$, thus finding no evidence for any transverse polarization.

6. Discussion and conclusions

The OPAL vector meson measurements, together with some recent DELPHI [22] results, clearly establish that leading vector mesons, other than the B^*, are spin-aligned with a preference for the helicity-zero state. A number models relevant to these observations are discussed in [1, 2, 22]. A simple statistical model based on spin counting [23] fits the B^* measurements; however the maximum value of ρ_{00} in this model is 0.5, which occurs when there is no production of pseudoscalar mesons containing the primary quark.

A QCD-inspired model [24] predicts ρ_{00}= 0 for leading vector mesons in the limit that quark and meson masses and transverse momenta can be neglected. However, if vector-meson production is considered as arising from a helicity-conserving process $q \to q$V, then ρ_{00}= 1 is expected [23]. In the firmly-based and generally successful LUND string model [25] of hadron formation, no spin alignment of vector mesons is expected [25], and the same is true of the cluster model of HERWIG [26]. So although these QCD models have enjoyed a good measure of success in describing the LEP 1 data, the results on vector meson spin alignment still await a firm theoretical interpretation.

The OPAL measurements of small, negative values of the off-diagonal element Re ρ_{1-1} are in agreement with coherence in the primary $q\overline{q}$ production and fragmentation. In the case of the K^{*0}, the numerical values are in agreement with a recent theory [1] based on the standard model.

While the vector meson spin-alignment results remain to be explained, the measurements of Λ polarization in the Z^0 decay data are consistent with a simple constituent quark model whereby primary quark polarization is transferred to a final state hyperon during hadronization.

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REFERENCES

[1] M. Anselmino, M. Bertini, F. Murgia and P. Quintairos, "Off-diagonal helicity density matrix elements for vector mesons produced at LEP", preprint hep-ph/9704420, to appear in *Eur. Phys. Jour.* **C**; M. Anselmino, Spin effects in vector meson production at LEP, preprint hep-ph/9802435, these proceedings.

[2] OPAL Coll., G. Alexander *et al.*, *Z. Phys.* **C74**, 437 (1997).

[3] Particle Data Group, R.M. Barnett *et al.*, *Phys. Rev.* **D54**, 1 (1996).

[4] OPAL Coll., K. Ahmet *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A305**, 275 (1991).

[5] P.P. Allport *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A324**, 34 (1993); P.P. Allport *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A346**, 476 (1994).

[6] M. Hauschild *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A314**, 74 (1992).

[7] T. Sjöstrand, *Comp. Phys. Commun.* **39**, 346 (1986); T. Sjöstrand, M. Bengtsson, *Comp. Phys. Commun.* **43**, 367 (1987); T. Sjöstrand, CERN manual CERN-TH.7112/93, Geneva 1993.

[8] OPAL Coll., M.Z. Akrawy *et al.*, *Z. Phys.* **C47**, 505 (1990); The JETSET7.4 parameters were tuned as described in OPAL Coll., G. Alexander *et al.*, *Z. Phys.* **C69**, 543 (1996).

[9] J. Allison *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A317**, 47 (1992).

[10] OPAL Coll., K. Ackerstaff *et al.*, *Z. Phys.* **C74**, 413 (1997).

[11] OPAL Coll., G. Alexander *et al.*, *Z. Phys.* **C66**, 19 (1995).

[12] OPAL Coll., G. Alexander *et al.*, *Z. Phys.* **C73**, 379 (1997).

[13] OPAL Coll., R. Akers *et al.*, *Z. Phys.* **C67**, 27 (1995).

[14] OPAL Coll., K. Ackerstaff *et al.*, *Phys. Lett.* **B412**, 210 (1997).

[15] ALEPH Collaboration, D. Buskulic *et al.*, *Phys. Lett.* **B374**, 319 (1996).

[16] G. Gustafson, J. Häkkinen, *Phys. Lett.* **B303**, 350 (1993).

[17] B. Andersson *et al.*, *Physica Scripta* **32**, 574 (1985).

[18] OPAL Collaboration, P.D. Acton *et al.*, *Z. Phys.* **C58**, 387 (1993); OPAL Collaboration, R. Akers *et al.*, *Z. Phys.* **C69**, 543 (1996).

[19] P. Edén, G. Gustafson, *Z. Phys.* **C75**, 41 (1997); P. Edén, "A program for baryon generation and its applications to baryon fragmentation in DIS", Lund Preprint LU TP 96-29.

[20] OPAL Coll., G. Alexander *et al.*, "Polarization and forward-backward asymmetry of Λ baryons in hadronic Z^0 decays", preprint CERN-PPE/97-104, to appear in *Eur. Phys. Jour.* **C**.

[21] A. Kotzinian, A. Bravar, D. von Harrach, "Λ and $\overline{\Lambda}$ Polarization in Lepton Induced Processes", preprint hep-ph 9701384, submitted to *Eur. Phys. Jour.* **C**.

[22] DELPHI Coll., P. Abreu *et al.*, *Phys. Lett.* **B406**, 271 (1997).

[23] J.F. Donoghue, *Phys. Rev.* **D19**, 2806 (1979).

[24] J.E. Augustin, F.M. Renard, *Nucl. Phys* **B162**, 341 (1980).

[25] B. Andersson, G. Gustafson, G. Ingelman, T. Sjöstrand, *Phys. Rep.* **97**, 31 (1983).

[26] G. Marchesini *et al.*, *Comp. Phys. Commun.* **67**, 465 (1992).