

POLARIZATION AND SPIN ALIGNMENT IN MULTIHADRONIC Z^0 DECAYS

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The large statistics of millions of hadronic Z^0 decays, accumulated by the four LEP experiments between 1989 and 1995, allowed for detailed investigations of the fragmentation process. Inclusive Λ_b baryons and Λ hyperons at intermediate and high momentum have been found to show longitudinal polarization. This may be related to the primary quark and antiquark polarization and the hadronization mechanism which produces the leading baryons. Helicity density-matrix elements have been measured for a variety of vector mesons produced inclusively in hadronic Z^0 decays. The diagonal elements of some of the light mesons and the $D^{*\pm}$ show a preference for a helicity-zero state if the meson carries a large fraction of the available energy. The mechanism which produces such spin alignment in the non-perturbative hadronization of the primary partons to the vector mesons is so far unexplained. For the B^* , the results are consistent with no spin alignment, which is expected in a picture based on HQET. For some meson species non-diagonal elements have been measured indicating coherence phenomena due to final-state interaction between the primary quark and antiquark.

1 Introduction

Between 1989 and 1995, the four LEP collaborations have recorded over 16 million hadronic Z^0 decays which allow for detailed studies of the hadronization process.

Primary quarks produced in e^+e^- annihilations around the Z^0 pole are strongly left-handed with longitudinal polarizations of approximately -0.91 for down-type quarks and -0.64 for up-type quarks.

A measurement of the leading baryon polarization in self-analysing weak decay modes can be used to investigate the polarization transport in the fragmentation process and gives useful new information on the dynamics of the hadronization process.

The vector mesons are $q\bar{q}$ systems of total spin one without angular momentum, and any alignment of the meson spin must arise at least in part from the dynamics of the hadronization phase.

2 Principles of the Measurements

To measure the polarization of Λ baryons, the decay angular distribution of the proton in the hyperon rest frame in the decay $\Lambda \rightarrow p\pi$ is analysed.^{1,2}

The Λ_b polarization is studied using its semileptonic decays with a Λ hyperon reconstructed in the final state.^{5,6,7} The energy spectra of the charged lepton and of the neutrino, determined by the missing energy in the hemisphere containing the Λl system, are sensitive to the polarization.

Spin alignment of vector mesons can be described in terms of the spin density matrix $\rho_{\lambda\lambda'}$, which is a 3x3 Hermitian matrix with unit trace, usually defined in the helicity base. As described in¹² the elements of the helicity density matrix can be measured using the angular distribution of the corresponding vector meson decay products. The diagonal elements, limited by $0 \leq \rho_{\lambda\lambda} \leq 1$, represent the relative intensities of the three helicity states $\lambda = -1, 0, +1$. In parity conserving decays, only one diagonal element is measurable. Thus, a state with no spin alignment corresponds to $\rho_{00} = 1/3$. The off-diagonal elements, for example ρ_{1-1} , measure the correlation between states with different helicities.

3 Polarization of Baryons

3.1 Polarization of Λ hyperons

Figure 1 shows the ALEPH¹ and OPAL² measurements of the Λ polarization for different ranges of the Λ energy scaled to the beam energy ($z \equiv x_E$). For $x_E > 0.3$, the ALEPH collaboration measures a polarization of -0.32 ± 0.07 consistent with the corresponding OPAL result of $P_L = -0.329 \pm 0.076$.

A model of Gustafson and Häkkinen³ is used to calculate the expected x_E dependence of the polarization using the JETSET and HERWIG Monte Carlo programs to determine the Λ production rates from several different sources. In this model the following assumptions were made:

- the spin of the Λ is determined by the spin of the s quark and directly produced Λ are polarized 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 as given by the SU(6) model;
- any polarization is lost if a primary u or d quark becomes a constituent quark of the Λ , forming a spin-0 ud diquark;

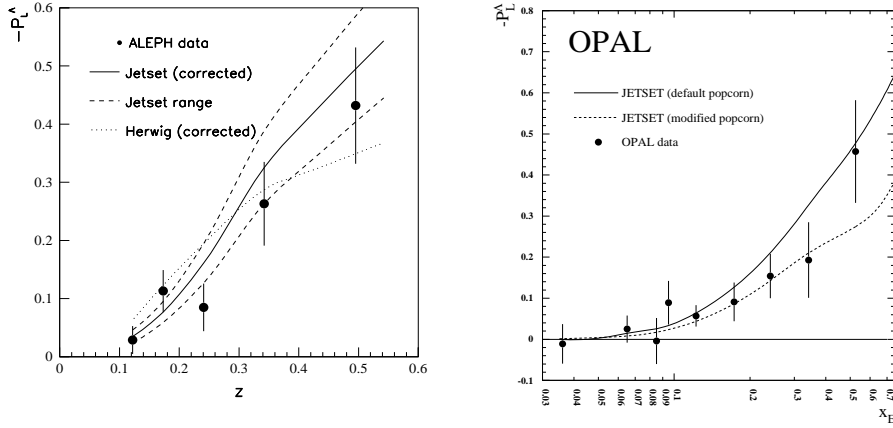


Figure 1. Measured longitudinal polarization of Λ hyperons as a function of the scaled energy. The curves show the prediction of a model discussed in the text.

- Λ hyperons containing only quarks produced in the fragmentation are not polarized.

This relatively simple constituent quark model fits the observations. This supports the idea that the primary strange quark polarization is transferred completely to the formed final state hyperon during hadronization.

However, other interpretations⁴ of the Λ polarization are by no means disfavoured.

3.2 Polarization of Λ_b baryons

Λ_b polarization has been studied by ALEPH⁵, DELPHI⁶ and OPAL.⁷

Table 1. Λ_b polarization measurements.

$-0.23^{+0.24}_{-0.20}(\text{stat.})^{+0.08}_{-0.07}(\text{syst.})$	ALEPH
$-0.49^{+0.32}_{-0.30}(\text{stat.}) \pm 0.17(\text{syst.})$	DELPHI
$-0.56^{+0.20}_{-0.13}(\text{stat.}) \pm 0.09(\text{syst.})$	OPAL

A model of Falk and Peskin,⁸ based on HQET, taking account of b baryons

proceeding through intermediate states such as Σ_b and Σ_b^* gives a range of expected polarization between -0.54 and -0.88 .⁷

The experimental results given in Table 1 agree with each other and with the hypothesis of the HQET model that there is no loss of the initial b quark polarization during the fragmentation.

4 Vector Meson Helicity Density Matrix Elements

Helicity density-matrix elements have been measured by ALEPH,⁹ DELPHI^{10,11} and OPAL^{12,13,14} for various meson species. As an example,

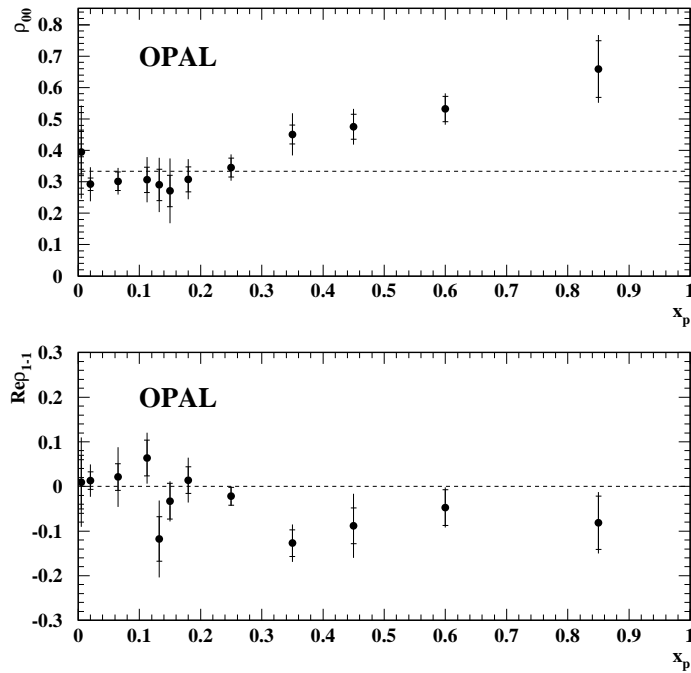


Figure 2. K^{*0} helicity density matrix elements, ρ_{00} and $\text{Re}(\rho_{1-1})$ as functions of x_p .

the results of the inclusive $K^*(892)^0$ analysis¹³ are shown in Fig. 2. At large momentum where the K^* most likely contains a primary quark from the Z^0

decay, the results show a clear deviation from $\rho_{00} = 1/3$ and $\text{Re}(\rho_{1-1}) = 0$.

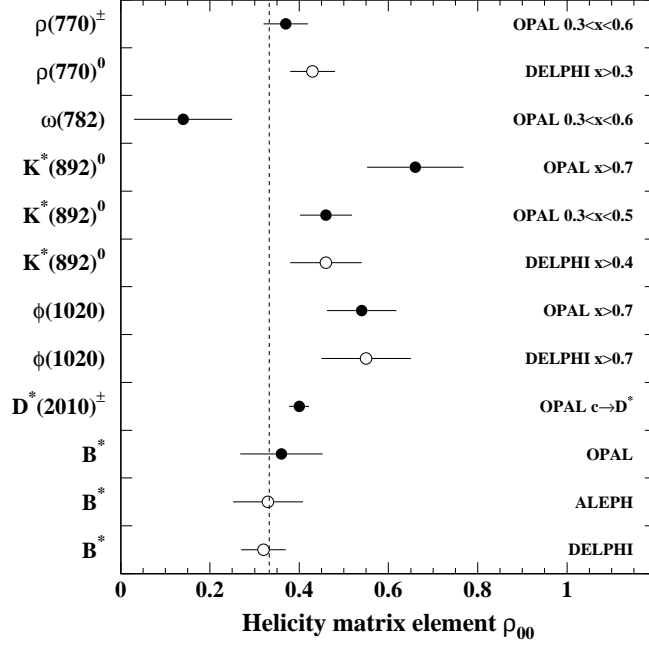


Figure 3. Values of helicity density matrix element ρ_{00} for various meson species.

Figure 3 summarizes the measurements of the matrix element ρ_{00} . B^* mesons show no deviation from equal population of the three helicity states. The $D^*(2010)^\pm$ sample consists of both directly produced $c \rightarrow D^*$ mesons and those from excited charm hadron decays. A value of $\rho_{00} = 0.40 \pm 0.02$ indicates an enhanced production in the zero helicity state. The results for the lighter leading mesons, which are likely to contain the primary polarized quark, are not completely conclusive. However, in general there is a clear indication for a production in the helicity zero state.

A statistical model based on spin counting⁸ fits the B^* measurements. A QCD-inspired model¹⁶ predicts $\rho_{00} = 0$ for leading vector mesons in the limit that quark and meson masses and transverse momentum can be neglected. If

the vector meson production is considered as arising from a helicity-conserving process $q \rightarrow qV$, then $\rho_{00} = 1$ is predicted.¹⁵ In the generally successful JET-SET string model of hadron formation, no spin alignment is expected and the same is true for the HERWIG cluster model. The pattern of observations would benefit from more experimental measurements, and awaits a firm theoretical interpretation.

For some mesons OPAL^{12,13} and DELPHI¹¹ have measured non-diagonal helicity density matrix elements. Whilst the OPAL collaboration has some evidence for small negative values of $\text{Re}(\rho_{1-1})$ for the D^* , $\phi(1020)$ and $K^*(892)^0$ mesons, which is in agreement with some theoretical expectations¹⁷ that coherence phenomena due to final-state interaction between the primary quark and antiquark play a role in fragmentation, the DELPHI results for ρ^0 , $K^*(892)^0$ and $\phi(1020)$ are consistent with zero.

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