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Λ_b POLARIZATION IN THE DELPHI EXPERIMENT AT LEP * **

P. Brückman

Institute of Nuclear Physics
Kawiory 26a, 30-055 Cracow, Poland

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The Standard Model predicts that at LEP at the Z^0 pole b quarks are produced with a high (≈ -0.94) longitudinal polarization. According to the HQET predictions substantial part of it should be transferred to the ground baryonic state Λ_b . The polarization is experimentally accessible by measuring the charged lepton and neutrino energy spectra from the Λ_b semileptonic decays. From the data sample of ≈3 million hadronic Z^0 decays collected by DELPHI in the years 1993–1995 271±22 Λ_b semileptonic decay candidates are selected using Λ^0-lepton correlations giving rise to the polarization value of[1]: $P_{\Lambda_b} = -0.48^{+0.35}_{-0.27}(\mathrm{stat.})^{+0.15}_{-0.13}(\mathrm{syst.})$.

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1. Introduction

The polarization of fermions produced in the reaction $e^+e^- \to Z^0 \to f\bar{f}$ is precisely predicted in the framework of the Standard Model. In the case of unpolarized e^+e^- beams the mean polarization of emerging fermions is [2]:

$$\begin{aligned}
\langle P_{e,\mu,\tau}\rangle &= -\mathcal{A}_e \cong -0.16\,,\\
\langle P_{u,c}\rangle &= -\mathcal{A}_u \cong -0.66\,,\\
\langle P_{d,s,b}\rangle &= -\mathcal{A}_d \cong -0.94\,. \qquad (1)
\end{aligned}$$

The down-type quarks (and b among them) are most strongly polarized. Moreover, their polarization is fairly stable over the whole range of the production angle.

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[1] This report is directly based on the Ph.D. thesis prepared by the author. For details of the analysis please consult the dissertation [1].

Λ_b is the lightest b-baryon and consists of three valence quarks (bud). Its mass has been determined to be $(5621 \pm 4 \pm 3)\mathrm{MeV/c^2}$ [3]. The light pair (ud) forms a light diquark of a total spin $S = 0$: $|\uparrow\rangle_b|\mathrm{S}=0\rangle_{qq}$. Therefore, total spin of the Λ_b is carried by the b quark. In the heavy quark limit (HQET) a b quark hadronizing directly to a Λ_b should pass its complete initial polarization to the baryon and then conserve it throughout the whole Λ_b lifetime. In real life however, a large fraction of Λ_b's can be produced indirectly through the heavier Σ_b and Σ_b^* states:

$$\begin{aligned} b &\longrightarrow \Sigma_b \longrightarrow \Lambda_b^0 + \pi\,,\\ b &\longrightarrow \Sigma_b^* \longrightarrow \Lambda_b^0 + \pi\,. \end{aligned} \tag{2}$$

Processes (2) are predicted to lead to a substantial depolarization of the heavy quark. A detailed discussion of different scenarios of the indirect hadronization is given in [4, 5].

In the Born approximation of the free quark the differential rate of the decay $b \to c + l + \bar{\nu}$ is proportional to a simple matrix element [6]:

$$d\Gamma^{(0)} \;\sim\; |\mathcal{M}^{(0)}|^2 d\boldsymbol{R}_3\,, \tag{3}$$

where

$$|\mathcal{M}^{(0)}|^2 = (\boldsymbol{cl})\,((\boldsymbol{b} - m_{\mathrm{b}}\boldsymbol{S}_{\mathrm{b}})\boldsymbol{\nu})\;. \tag{4}$$

$\boldsymbol{b}$,$\boldsymbol{c}$,$\boldsymbol{l}$ and $\boldsymbol{\nu}$ denote four-momenta of the involved fermions and $\boldsymbol{S}_b$ is the b quark spin four-vector. The matrix element exhibits a nice factorization of the spin direction component [7]:

$$|\mathcal{M}^{(0)}|^2 = |\mathcal{M}^{(0)}_{\mathrm{unpol}}|^2\,(1 + P\cos\theta)\,, \tag{5}$$

where θ is the angle between the neutrino momentum and the spin quantization axis. First order QCD corrections for the process (4) have been calculated [6–8]. A virtual gluon exchange and a real gluon emission contribute to the total matrix element $|\mathcal{M}|^2 = |\mathcal{M}^{(0)}|^2 + |\mathcal{M}^{\mathrm{exchange}}|^2 + |\mathcal{M}^{\mathrm{emission}}|^2$. *A priori* the correction terms do not retain the straightforward factorization (5) but fortunately even in this case the angular dependent and independent parts cancel to a large extent in the ratio. In practice factorization is violated only at the level of one percent and hence having absorbed all corrections to the overall normalization we can assume that

$$|\mathcal{M}|^2 \cong |\mathcal{M}_{\mathrm{unpol}}|^2(1 + P\cos\theta)\,. \tag{6}$$

In particular the Λ_b polarization in the Monte Carlo simulation is reproduced using the approximation (6). It can be argued that when going to real heavy baryon decays the dynamics of the reaction $\Lambda_b \to \Lambda_c l\nu$ remains identical with the free quark case discussed above [9]. This approximation is derived from the leading order of the Heavy Quark Effective Theory.

2. Determination of the Λ_b polarization

Direct observation of the angular distributions in the Λ_b rest frame is impossible. However, thanks to a large boost of the Λ_b in the laboratory frame the forward-backward asymmetry of the decay product can be directly expressed in terms of a shift in the average value of its energy spectrum in the laboratory frame:

$$2\langle E\rangle_{\mathrm{LAB}} \cong \langle E + p_{\|}\rangle_{\mathrm{LAB}} = \langle (1+\beta)\gamma\rangle \langle E + p_{\|}\rangle_{\Lambda_b \mathrm{rest}} . \tag{7}$$

Since the average values of charged lepton and neutrino spectra are respectively anticorrelated and correlated with the polarization the variable defined as:

$$y = \frac{\langle E_l\rangle}{\langle E_\nu\rangle} \tag{8}$$

turns out to be highly sensitive to Λ_b^0 polarization [6, 10]. Moreover, this observable is explicitly independent of fragmentation uncertainties since the boost factor cancels out in the ratio (8).

Experimentally observed energy spectra undergo several deformations because of detector response and selection cuts. To compensate for these effects the variable y obtained from the data has been normalized to the one extracted from an explicitly unpolarized simulated data. Therefore, the final observable is defined as:

$$R_y = \frac{y^{\mathrm{DATA}}}{y^{\mathrm{MC}}} . \tag{9}$$

Any deviation of the R_y from unity observed in the background subtracted Λ_b signal is attributed to the Λ_b polarization.

2.1. Λ_b signal

The analysis is based on $\approx 3 \times 10^6$ hadronic Z^0 decays collected by the DELPHI detector [11] in the years 1993–1995. The sample of Λ_b semileptonic decays is extracted by selecting prompt Λ^0 hyperons together with a charged lepton (electron or muon) in the same event hemisphere. Λ^0 candidates are reconstructed in the channel $\Lambda \to \mathrm{p}\pi^-$, using reconstructed distinct vertices of two oppositely charged tracks. The b-baryon signal is uniquely related to Λl^- (or $\bar{\Lambda} l^+$) correlations (R.S.) and all background events have no physically preferred correlation. It has been proved in the MC that the W.S. event sample reproduces well the background under the Λ_b signal contained in the R.S. events. The excess of R.S. correlations over the opposite ones (W.S.) in the Λ^0 mass peak amounts to 271 ±22 and can be attributed to the Λ_b signal (see Fig. 1).

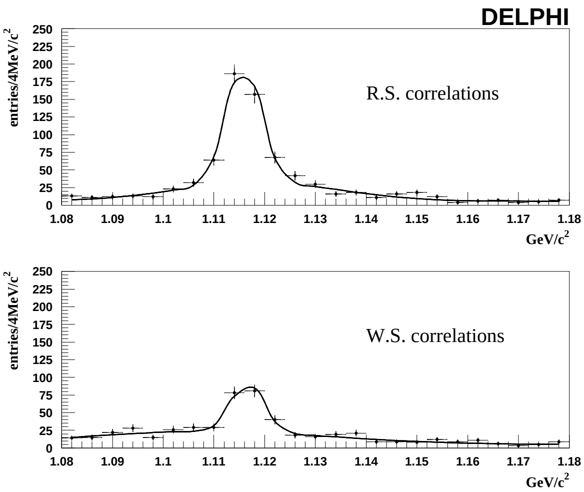

Fig. 1. (pπ) mass distributions for Λ^0 candidates correlated with an identified high p$_T$ lepton in 1993–1995 data. The excess of *right-sign* over *wrong-sign* events is attributed to the b baryon signal. The curves are the result of the double-Gaussian fits.

The average charged lepton energy and the average neutrino energy for the genuine Λ_b component are obtained using the direct subtraction of the W.S. sample from the R.S. one: $\langle E_{l,\nu}\rangle = \frac{1}{1-f_{bck}}(\langle E_{l,\nu}^{\mathrm{R.S.}}\rangle - f_{bck}\langle E_{l,\nu}^{\mathrm{W.S.}}\rangle)$ where $\langle E_{l,\nu}^{\mathrm{R.S.}}\rangle$ and $\langle E_{l,\nu}^{\mathrm{W.S.}}\rangle$ are the average charged lepton or neutrino energies measured in the R.S. and in the W.S. samples respectively. f_{bck} is the background fraction defined as $f_{bck} = \frac{\mathrm{N^{W.S.}}}{\mathrm{N^{R.S.}}}$ where $\mathrm{N^{R.S.}}$ and $\mathrm{N^{W.S.}}$ are the numbers of selected events found in the R.S. and W.S. samples.

2.2. Neutrino energy reconstruction

The neutrino energy is measured as a missing energy (E_{miss}) in the hemisphere containing the $\Lambda^0 l$ system (event hemisphere). The neutrino energy is obtained from:

$$\begin{aligned} E_\nu &\approx E_{\mathrm{miss}} = E_{\mathrm{TOT}} - E_{\mathrm{vis}}^{\mathrm{corr}}\,, \\ E_{\mathrm{TOT}} &= \frac{\sqrt{s}}{2} + \frac{(M^{\mathrm{event}})^2 - (M^{\mathrm{oppo}})^2}{2\sqrt{s}}\,, \end{aligned} \tag{10}$$

where $E_{\mathrm{vis}}^{\mathrm{corr}}$ is the sum of all charged track energies and neutral calorimeter energy deposits in the event hemisphere (E_{vis}) corrected for the detector inefficiencies. E_{TOT} is the total energy available in the event hemisphere.

The lower equation results directly from the four-momentum conservation applied to the entire event. M^{event} and M^{oppo} are the event hemisphere invariant mass and the opposite hemisphere invariant mass respectively. $\sqrt{s}$ denotes the total energy in the center of mass of the colliding e^+e^- (E_{CM}) and is equal to the Z^0 mass.

From the Monte Carlo the fitted resolution of the neutrino energy reconstruction amounts to 4.2 GeV.

3. Results & implications

The Λ_b polarization is determined from the value of the R_y observable. The Λ_b polarization is found to be:

$$P_{\Lambda_b} = -0.48\ ^{+0.35}_{-0.27}(\text{stat.})\ ^{+0.15}_{-0.13}(\text{syst.})\,. \tag{11}$$

It is clearly seen that the statistical error is dominating over the systematic uncertainties.

To crosscheck consistency of the experimental procedure an identical polarization analysis was performed on the sample of semileptonic decays of B^0 mesons via the process $B^0 \longrightarrow D^* l^+ \nu_l$. The D^* mesons are reconstructed in the channel $D^* \to D^0 \pi^+_{\text{soft}}$ where $D^0 \to K^-\pi^+$. B^0 mesons being scalar particles cannot retain any polarization of the primary b quark. Hence, the polarization measured on the B^0 sample should be consistent with zero. The obtained result is:

$$P_B = -0.07^{+0.23}_{-0.19}\,, \tag{12}$$

where the quoted error is purely statistical. The result is compatible with expected lack of polarization in the b-meson sector.

The latest ALEPH measurement on Λ_b polarization submitted to the ICHEP'96 conference comprises all LEP1 statistics (≈4 million Z^0) collected in the period 1991–1995 [12].

From this data sample 559±34 Λ_b candidates were selected using $(\Lambda^0\pi^+)l^-$ correlations. ALEPH determines the Λ_b polarization to be:

$$P_{\Lambda_b} = -0.30^{+0.19}_{-0.16}(\text{stat.}) \pm 0.06(\text{syst.})\,.$$

The ALEPH and DELPHI results are compatible within the statistical uncertainty. The combined value of the Λ_b polarization reads:

$$P_{\Lambda_b} = -0.36^{+0.17}_{-0.14}(\text{stat.})^{+0.07}_{-0.06}(\text{syst.})$$

giving evidence for a substantial Λ_b depolarization.

4. Conclusions

The simplest explanation of the depolarization phenomenon is based on the substantial contribution of the cascade: $b \to \Sigma_b^{(*)} \to \Lambda_b$. Evidence for $\Sigma_b^{(*)}$ baryon production has been observed in the DELPHI experiment [13]. The measured production rate is $f(b \to \Sigma_b^{(*)}) = (4.8 \pm 1.6)\%$. When combined with an ALEPH estimate of inclusive b-baryon production $f(b \to \text{baryons}) = (11.5 \pm 4.0)\%$ [14], this gives the fraction of $\Sigma_b^{(*)}$ in the total b-baryon production $f_{\Sigma_b} = (42 \pm 20)\%$. Figure 2 compares the experimental values with the theoretical predictions given in [4]. Two bands $w_1 = 0$ and $w_1 = 1$ correspond to two extreme spin alignment cases: spin of the diquark is orthogonal to the fragmentation axis ($w_1 = 0$) and spin of the diquark is parallel to the fragmentation axis ($w_1 = 1$). We emphasize that the above depolarization mechanism exists only if the Σ_b and Σ_b^* are distinct narrow resonances which seems to be the case according to the preliminary measurement of DELPHI.

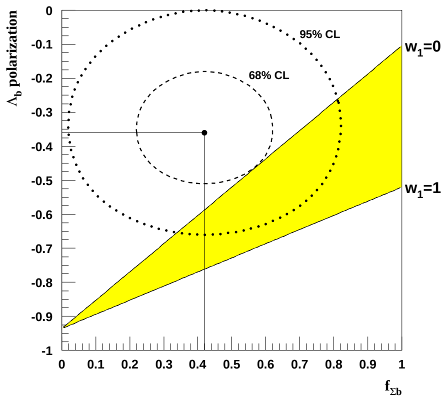

Fig. 2. Measured value of the Λ_b polarization and $\Sigma_b^{(*)}$ production as compared to the theoretical prediction.

A small diminution of the primary b quark polarization can be expected due to the value of the "effective coupling $\mathcal{A}_b$":

– Standard Model: $\mathcal{A}_b = 0.935$,

– experiment (from $\mathrm{A_{FB}}$ [15]): $\mathcal{A}_b = 0.890 \pm 0.029$.

Probably it would be justified to consider the latter number as the value of initial b polarization rather than the SM one.

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