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Heavy Quark Theory and *b*-polarisation at LEP

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1 Introduction

According to the standard model, b quarks from the Z resonance $e^+e^- \to Z \to \bar{b}b$ have almost complete longitudinal polarisation, given by [1]

$$P_L = \frac{2v_b a_b \beta(1+\cos^2\theta) + 2r_e(v_b^2 + a_b^2\beta^2)\cos\theta}{(v_b^2 + a_b^2)\beta^2(1+\cos^2\theta) + 2v_b^2(1-\beta^2) + 4r_e v_b a_b \beta\cos\theta} \tag{1}$$

where $v_b = -1 + 4x_W/3, a_b = 1, x_W = \sin^2\theta_W$, $r_e = (4x_W - 1)/(8x_W^2 - 4x_W + 1)$, $\beta^2 = 1 - 4m_b^2/m_Z^2$ and θ is the CM scattering angle of b relative to e^-. For x_W=0.23 this gives a mean value $< P_L >= -0.94$ with very little angular dependence. A small transverse polarization of order 0.02 is predicted in the scattering plane; there is no polarization normal to the plane if we neglect $\gamma - Z$ interference and loop corrections.

The question we address here is whether this big polarization can be exploited? Does it lead to new measurable effects and if so what can be learned from them?

We must first determine whether b-quark polarization can survive hadronization to give b-hadron polarization, and if so how to measure the latter through b-hadron decays. Finally we must estimate the size of the effects from models.

2 Hadronization

Hadronization to *mesons* is hopeless for our purposes. It is possible that high-spin mesons formed from b may retain some of the initial b-polarization, but they will decay by parity-conserving processes (that cannot give polarization-dependent asymmetries) down to a spin-0 B-meson that retains no spin information.

It is instructive however to consider how b-spin information is lost. Suppose a spin-up b combines with a spin-down $\bar{q}$ forming the state $b^\uparrow\bar{q}^\downarrow$. This is not an eigenstate of total spin S but can be decomposed into a sum of $S = 0$ and S=1 eigenstates:

$$b^\uparrow\bar{q}^\downarrow = \frac{1}{\sqrt{2}}\left[\frac{b^\uparrow\bar{q}^\downarrow - b^\downarrow\bar{q}^\uparrow}{\sqrt{2}}\right] + \frac{1}{\sqrt{2}}\left[\frac{b^\uparrow\bar{q}^\downarrow + b^\downarrow\bar{q}^\uparrow}{\sqrt{2}}\right] \tag{2}$$

If we add a common space wave function, then these two terms represent a spin-0 meson and a spin-1 meson coherently superposed. If indeed the physical meson states were precisely degenerate (as in the $M_Q \to \infty$ limit of HQET), the time evolution of the S=0 and S=1 terms would be identical and the coherence would be preserved; the spin wave function would then remain $b^\uparrow\bar{q}^\downarrow$, the coherent superposition of meson states would preserve the b spin and total spin S would be irrelevant. In reality however $M_b \neq \infty$; the pseudoscalar B and vector B^* mesons have different masses and therefore different time evolutions; at times $t \gg (m_0 - m_1)^{-1}$ the $S = 0$ and S=1 amplitudes become effectively incoherent and the b-quark is depolarized over a period of time by spin-spin forces within the mesons (indeed the same forces that generate the $B - B^*$ mass splitting).

Hadronization to *b-baryons* is more promising. The Pauli principle implies that if a b-quark combines with a spin-0 combination of one u plus one d, a Λ_b is formed; if the light quark pair has spin 1 then Σ_b or Σ_b^* result with total spin 1/2 or 3/2 (see ref. 2 for explicit wavefunctions). The crucial feature of this system is that in the heavy quark limit the Σ_Q, Σ_Q^* become degenerate and some 200 MeV more massive than the Λ_Q with the result that they decay to Λ_Q by strong interaction, preserving the b polarization.

Suppose first that the polarized b quark picks up a spin-0 ud pair to form a "prompt" Λ_b. Due to its ud pair having spin-0, all of the Λ_b spin resides on the valence b-quark and we expect b-polarization to become Λ_b- polarization (in the heavy quark limit where b spin-flip is suppressed during hadronization). Suppose instead that the polarized b-quark had combined with a spin-1 ud pair. In this case we would have to decompose the bqq wavefunctions into superpositions of eigenstates of different total spin S=1/2, 3/2 (Σ, Σ^*). At $t > (\Delta m(\Sigma, \Sigma^*))^{-1}$ the b- quark would become depolarized in the Σ, Σ^* system for reasons analogous to those outlined for B, B^* mesons above (in the present case the depolarization is only partial). Subsequent decays to Λ_b would produce partially depolarized Λ_b.

However the near degeneracy of Σ_b, Σ_b^*, in contrast to their remoteness ($> m_\pi$) from the Λ_b causes the evolution or "decoherence" timescales ($\sim \Delta m^{-1}$) to be much longer than the timescale of strong decay. Furthermore, as the strong π decay involves only the ud quarks, the b polarization is transferred to the resulting Λ_b essentially unchanged. Hence coherence is preserved, b remains polarized, and the final Λ_b carries the initial b-quark polarization. These arguments apply for hadronization to excited $\Lambda_b, \Sigma_b, \Sigma_b^*$ states too.

To summarize, *whether b fragments directly to Λ_b or gets there indirectly by a fragmentation/decay chain, the heavy quark approximation suggests that initial b polarization becomes final Λ_b polarization.*

3 Decay modes

Semileptonic decays $\Lambda_b \to X_c \ell \bar{\nu}$ are sensitive to Λ_b polarization and have an inclusive branching fraction of about 20% (summing over $\ell = e, \mu$ and all X_c final states). To tag such events we would typically require lepton $p_T > 1$ GeV transverse to the jet axis plus evidence of charmed baryons in the decay products. The lepton distribution here has a forward/backward asymmetry along the polarization axis (essentially the jet axis) in the Λ_b rest-frame; for a given decay model this asymmetry directly measures the polarization, but unfortunately the neutrino's invisibility makes it impossible to reconstruct the rest-frame accurately. Alternatively, if we also know the distribution of Λ_b from a fragmentation model, we can predict the lab-frame distribution of lepton longitudinal momentum fraction $x(\ell) = 2p_L(\ell)/m_Z$; the latter retains some sensitivity and its mean value $< x(\ell) >$ is different for polarized and unpolarized Λ_b. However, to interpret $x(\ell)$ distributions we need reliable models for both fragmentation and decay.

The decay $\Lambda_b \to \psi\Lambda$ has some nicer properties but unfortunately a small branching fraction of order 1%. Also, to identify such events we need subsequent $\psi \to \ell^+\ell^-$ and $\Lambda \to p\pi^-$ decays that give further suppression by 0.088, but at least the Λ_b rest-frame can then be reconstructed (and hence $b \to \Lambda_b$ fragmentation measured, thereby providing more input for the semileptonic analysis). In this frame the decay angular distribution has a forward/backward asymmetry along the jet axis that directly measures the Λ_b polarization. The final Λ polarization, measurable through an asymmetry in the $\Lambda \to p\pi^-$ decay, also has some sensitivity to the initial Λ_b polarization in principle.

Similar remarks apply to $\bar{b} \to \bar{\Lambda}_b$ fragmentation and decay, assuming CP invariance. If the b polarization increases $< x >$ for a given final particle f, then the $\bar{b}$ polarization increases $< x >$ equally for the corresponding decay product $\bar{f}$.

4 Models

We use models simply to provide concrete illustrations; they do not represent the most detailed possible analysis. For fragmentation we take the Peterson model[3] with $z = (E+p_L)_{hadron}/(E+p_L)_{quark}$ and parameter ϵ_b=0.05 consistent with LEP data[4], assuming all b-hadrons have the same z distribution.

A. Semileptonic Λ_b decay. The spectator model treats inclusive semileptonic decay like free b-quark decay $b \to c\ell\bar{\nu}$; for simplicity we omit refinements such as Fermi motion and QCD corrections,[5] and set $m_b = m_{\Lambda b} = 5.64$ GeV with $m_c = m_{\Lambda_c} = 2.285$ GeV to get the correct lepton kinematic limits. We require $p_T(\ell) > 1$ GeV for tagging. In the Λ_b rest-frame we then obtain a forward-backward lepton asymmetry $A_{FB} = (F - B)/(F + B) = -0.12\ P_L(b)$, where the parent Λ_b momentum defines the backward direction. This asymmetry is not directly accessible, however, because the Λ_b rest-frame cannot be reconstructed in general (however, since the Λ_b momentum direction is known approximately, the event can be reconstructed approximately if all the hadronic decay products are identified).

If we integrate over a distribution of Λ_b rest-frames predicted from Peterson fragmentation, the mean lepton longitudinal momentum fraction is

$$
\begin{aligned}
< x(\ell) > &= 0.312 \quad (-94\% \text{ polarized } \Lambda_b), \\
&= 0.289 \quad (\text{unpolarized } \Lambda_b).
\end{aligned} \tag{3}
$$

showing a 6% difference. Remember however that there is no unpolarized Λ_b sample to compare with; we can only compare with B-meson semileptonic decays. A difference in $< x(\ell) >$ could then be due not only to polarization but also to differences in fragmentation function or decay matrix elements (Cautionary example: if we use the same model for B-meson decay, but with $m_b = m_B$ and $m_c = m_D$ to get correct lepton kinematic limits, we obtain $< x(\ell) > = 0.309$ in contrast to eq (3b)).

B. $\Lambda_b \to \psi\Lambda$ spectator model[6]. Here we use the matrix elements of free quark decay $b \to c\bar{c}s$, simply constraining the $c\bar{c}$ invariant mass to lie near ψ (we take 3.0 GeV $< m(c\bar{c}) <$ 3.2 GeV). We omit Fermi motion[7] and take $m_b = m_{\Lambda b}$, m_c=1.5 GeV and $m_s = m_\Lambda$ to get the right ψ kinematics, neglecting the mass of the spin-0 spectator diquark. This is really an inclusive model; it includes contributions from ψ' and χ states that decay to ψ, as well as Λ^* formation. In the Λ_b rest-frame this model predicts a forward-backward asymmetry for ψ:

$$
A_{FB} = \frac{N(\theta < \frac{\pi}{2}) - N(\theta > \frac{\pi}{2})}{N(\theta < \frac{\pi}{2}) + N(\theta > \frac{\pi}{2})} = +0.23\ P_L(b) \tag{4}
$$

where θ is the decay angle of ψ and the negative z-axis ($\theta = \pi$) is defined by the parent Z^0 momentum.

In this model the final s-quark helicity (that we might associate with the Λ helicity) is close to $-\frac{1}{2}$ irrespective of the initial b spin, because of the standard $V-A$ coupling. This suggests that the Λ polarization is insensitive to Λ_b polarization and is a poor way to analyze the latter.

We could tighten this model by requiring spin-1 and $m(c\bar{c}) = m_\psi$ in the $c\bar{c}$ channel and by identifying the spin of s with the spin of Λ. This would give an effective $\bar{\Lambda}\gamma^\mu(1-\gamma_5)\Lambda_b\psi_\mu$ coupling, which is a particular case of the next model.

C. $\Lambda_b \to \psi\Lambda$ exclusive model. In the heavy-quark effective theory one is led to an effective coupling of the general form[8]

$$L = -\bar{\Lambda}[f_1(\omega)\gamma^\mu(1-\gamma_5) + f_2(\omega)\not{v}\gamma^\mu(1-\gamma_5)]\Lambda_b\psi_\mu \tag{5}$$

where $v = p_{\Lambda b}/m_{\Lambda b}$ is the velocity 4-vector of Λ_b, $\omega = (p_{\Lambda b}{\cdot}p_\Lambda)/(m_{\Lambda b}m_\Lambda) = 1.86$ is the scalar product of Λ_b and Λ velocities, and the form factors f_1 and f_2 are related by

$$\begin{aligned} f_1(\omega) &= (1 + \frac{\lambda}{2m_s}\frac{1}{1+\omega})G(\omega), \\ f_2(\omega) &= -\frac{\lambda}{2m_s}\frac{1}{1+\omega}G(\omega). \end{aligned} \tag{6}$$

We take $m_s = 0.5$ GeV. Apart from an unknown overall constant $G(\omega)$, the spin dependence of the $\bar{\Lambda}\psi\Lambda_b$ coupling is thus specified by one mass parameter λ, expected to be of order 0.7 GeV and probably positive.

In general the decay angular distribution in the Λ_b rest-frame has the form

$$d\Gamma_{\Lambda b}/d\cos\theta = \frac{1}{2}\Gamma_{\Lambda b}(1 + aP_{\Lambda b}\cos\theta) \tag{7}$$

where θ is the ψ angle as in Eq. (4) and $P_{\Lambda b} = -0.94$ is the initial Λ_b polarization along the z axis. To address Λ polarization effects, we decompose $\Gamma_{\Lambda b} = \Gamma^+_{\Lambda b} + \Gamma^-_{\Lambda b}$ where $\Gamma^\pm_{\Lambda b}$ are the partial widths for decay to Λ helicities $\pm\frac{1}{2}$ in the Λ_b rest-frame, with general forms

$$d\Gamma^\pm_{\Lambda b}/d\cos\theta = \frac{1}{4}\Gamma_{\Lambda b}(1 + aP_{\Lambda b}\cos\theta \pm b \pm cP_{\Lambda b}\cos\theta) \tag{8}$$

If we boost these Λ helicity $\pm\frac{1}{2}$ states to the Λ rest-frame, their $\Lambda \to p\pi^-$ decay angular distributions are $d\Gamma^\pm_\Lambda/d\cos\xi = \frac{1}{2}\Gamma_\Lambda\ (1 \pm \alpha\cos\xi)$. Here ξ is the proton polar angle, the negative z- axis ($\xi = \pi$) is defined by the parent Λ_b momentum vector in the Λ rest-frame, and the asymmetry parameter is α=0.64. Combining this with Eq (8) we obtain the joint θ, ξ decay distribution

$$d\Gamma_{\Lambda b}/d\cos\theta d\cos\xi = \frac{1}{4}\Gamma_{\Lambda b}(1 + aP_{\Lambda b}\cos\theta + \alpha b\cos\xi + \alpha cP_{\Lambda b}\cos\theta\cos\xi). \tag{9}$$

Thus there is sensitivity to polarization $P_{\Lambda b}$ through the θ- asymmetry parameter a and through the $\theta - \xi$ correlation parameter c. The parameters are predicted to be

$$\begin{array}{llll} a = 0.19 & b = -0.99 & c = -0.19 & \text{for } \lambda = 0.7GeV \\ a = 0.21 & b = -0.92 & c = -0.16 & \text{for } \lambda = 0 \\ a = 0.26 & b = -0.74 & c = -0.07 & \text{for } \lambda = -0.7GeV. \end{array} \tag{10}$$

The corresponding forward/backward ψ asymmetry is $A_{FB} = \frac{1}{2}aP_{\Lambda b} \simeq -0.1$ in these examples, somewhat smaller than model B.

5 Event rates

Summing over LEP experiments there are already more than a million hadronic Z events. The arithmetic of fragmentation and decay gives approximately

$$\begin{array}{rcl} 10^6 \text{ hadronic } Z \text{ decays} & \rightarrow & 4 \times 10^5 b \text{ or } \bar{b} \text{ quarks} \\ & \rightarrow & 4 \times 10^4 \Lambda_b \text{ or } \bar{\Lambda}_b \text{ hadrons} \\ & \rightarrow & 4 \times 10^3 \Lambda_c \ell \nu \text{ decays with } p_T(\ell) > 1\ GeV \\ & \rightarrow & 70\ (\psi \rightarrow \ell\bar{\ell})(\Lambda \rightarrow p\bar{\pi}) \text{ decays} \end{array}$$

using the UA1 central value 1.8×10^{-3} for the product of $b \rightarrow \Lambda_b \rightarrow \psi\Lambda$ fragmentation and decay fractions[9].

With such a data sample and 100% detection efficiency one could measure the mean lepton longitudinal momentum fraction to a statistical accuracy ± 0.003 in semileptonic decays. Such precision could resolve the polarization effect in principle, but in practice we have no unpolarized Λ_b sample for comparison, and there are theoretical uncertainties (that may be as large as the effect) in using B-meson decays for comparison instead.

In $\Lambda_b \rightarrow \psi\Lambda$ decays, N events can measure the asymmetry A_{FB} to an accuracy $\pm 1/\sqrt{N} = \pm 0.12$ in the present example, not enough to establish an effect like that in Eq (4). To determine the asymmetry parameter a in Eq (7) we could measure $3 < \cos\theta > = aP_{\Lambda b}$ to an accuracy $\pm\sqrt{(3 - a^2 P_{\Lambda b}^2)/N} \simeq \pm 0.21$ for the examples in Eq (10), plainly not enough to establish the effects illustrated there; at least ten million hadronic Z decays would be needed to establish $aP_{\Lambda b} = -0.18$ at 3 standard deviations. To determine the correlation parameter c we could measure $9 < \cos\theta\cos\xi > = \alpha c P_{\Lambda b}$ to a statistical accuracy $\pm\sqrt{(9 - \alpha^2 c^2 P_{\Lambda b}^2)/N}$; ten million hadronic Z decays would then determine $cP_{\Lambda b}$ to $\pm$ 0.18.

6 Conclusions

(i) Λ_b baryons plausibly preserve the parent b-quark polarization.

(ii) Semileptonic Λ_b decay distributions are sensitive to this polarization and present statistics could in principle establish a polarization effect in $< x(\ell) >$. But there is no unpolarized Λ_b sample to compare with and comparing with semileptonic B-decays instead introduces theoretical uncertainties that may obscure the effect, unless more precise fragmentation and decay models can be developed.

(iii) The $\Lambda_b \rightarrow \psi\Lambda$ decay asymmetry is moderately sensitive to Λ_b polarization but model dependent; it would require much higher statistics than are presently available to establish an effect here. The angular correlation between Λ_b and Λ decay angles is less sensitive to Λ_b polarization. Eventual measurements on either of these effects would provide checks on the spin-dependence of $b \rightarrow \Lambda_b$ fragmentation and/or models of Λ_b decay.

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