Chapter 1

Theory

All present knowledge of the fundamental world of particles is, except for gravity, incorporated in the so-called Standard Model. Due to symmetries for particles consisting of a heavy quark and a light quark, which are exact in the limit of infinite mass of the heavy quark, an effective theory exists within the Standard Model: The Heavy-Quark Effective Theory (HQET) [1] with which this thesis is concerned. This chapter begins with a short outline of the Standard Model. This is followed by a description of the symmetry and the effective theory of heavy-quark physics. After that, the theoretical predictions and existing experimental results on the $B^{**}_{u,d}$ will be discussed. In the last section, the theoretical predictions and experimental results on the B^* are summarised.

1.1 The Standard Model

According to the Standard Model of particle physics, all the matter our world is made of consists of quarks and leptons. Both types of particles have spin-$\frac{1}{2}$ and are called fermions. They can be divided into three groups or families. The first family consists of the 'up' and 'down' quarks, the electron and the electron neutrino; the second family of the 'charm' and 'strange' quarks and the muon and muon neutrino; and the last family consists of the 'top' and 'bottom' (or 'beauty') quarks and the tau and tau neutrino.

The six quarks and at least three of the leptons carry mass[1]. The six quark masses and the three lepton masses are parameters in the Standard Model. The masses of the electron, muon and tau are well measured. The quark masses are not well known since quarks are confined, i.e., they can not be detected as single particles, but always combine to form mesons ($q\overline{q}$) or baryons (qqq). The masses are assumed to be in the range of 1.5-5 MeV for a u quark, 3-9 MeV for a d quark and 60-170 MeV for an s quark. From the mass of the mesons that contain a c or b quark one estimates a mass of 1.1-1.4 GeV for a c quark and 4.1-4.4 GeV for a b quark [4]. In recent measurements at Fermilab [5, 6], the mass of the top quark was found to be (173.8 ± 5.2) GeV, compatible with predictions using LEP precision electroweak data [7].

The particles which intermediate the forces of interaction between fermions are spin-1 particles, called bosons. There are four known forces, but only three of them are incorporated

[1]The masses of the other three leptons (neutrinos) were always assumed to be zero, but recent results from the Super-Kamiokande collaboration [2, 3] indicate an atmospheric neutrino flux ratio which is not one and depends on the zenith angle. This hints to neutrino oscillations, which are possible only if at least one of the neutrinos is not massless.

into the Standard Model. These are the strong, weak and electromagnetic interactions. Each interaction has its own mediator boson(s): gluon, Z^0 and $W^{\pm}$, and photon respectively. Each force interacts with its own strength and these so-called coupling constants are parameters of the Standard Model.

The so-called Higgs mechanism accounts for the masses of particles via spontaneous symmetry breaking, i.e., all massive particles obtain their mass by interaction with the Higgs field. The Higgs mass and the vacuum expectation value of the Higgs boson are further parameters.

The property distinguishing the six quarks is called flavour. The weak interaction does not conserve flavour. Therefore, the weak eigenstates of quarks are not the individual flavour states, but a mixture of those. By convention, the d, s, and b quarks, rather than the u, c and t quarks, are chosen to be mixed. The mixing is described in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [8]:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$
$$= \begin{pmatrix} c_1 & -s_1c_3 & -s_1s_3 \\ s_1c_2 & c_1c_2c_3 - s_2s_3e^{i\delta} & c_1c_2s_3 + s_2c_3e^{i\delta} \\ s_1s_2 & c_1s_2c_3 + c_2s_3e^{i\delta} & c_1s_2s_3 - c_2s_3e^{i\delta} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}.$$

Here, c_i and s_i are abbreviations of $\cos\theta_i$ and $\sin\theta_i$, respectively. The three mixing angles θ_i and the overall phase δ are again parameters of the Standard Model.

The Lagrangian formalism describes the dynamics of the interactions. From the Lagrangian, so-called Feynman rules are derived. These are used to calculate measurable quantities like interaction cross sections, particle lifetimes and other quantities in perturbation theory. In figure 1.1 a few of these rules are indicated, particularly those of importance for heavy quarks (see section 1.3 below).

The quark of interest for this thesis is the beauty or bottom quark. This is one of the so-called heavy-flavour quarks. The symmetry and the effective theory that describe heavy-quark physics is described in the next sections.

1.2 Symmetries in QCD and heavy quark symmetry

There are several review articles written about HQS (Heavy Quark Symmetry), as references [9–13] testify. A summary is given here. It is very difficult to make predictions in the theory of the strong interactions called Quantum Chromo Dynamics (QCD) based on analytical calculations. However, the existence of symmetries makes it possible to approximate certain physical quantities. A well-known symmetry is isospin symmetry. It arises since the mass difference of the light quarks $m_{\mathrm{d}} - m_{\mathrm{u}}$ is much smaller than the masses associated with confinement, set by the QCD scale Λ_{QCD}. Predictions based on isospin symmetry would be exact in the limit $m_{\mathrm{d}} - m_{\mathrm{u}} \rightarrow 0$. In the real world this mass difference is not zero. To correct for this fact, an expansion in the small parameter $(m_{\mathrm{d}} - m_{\mathrm{u}})/\Lambda_{\mathrm{QCD}}$ and the electromagnetic coupling constant α can be made. When the s quark is included, the SU(3) flavour symmetry is obtained, but the corrections are larger since $(m_{\mathrm{s}} - m_{\mathrm{d}})/\Lambda_{\mathrm{QCD}}$ is not as small.

Another well known symmetry is chiral symmetry $\mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}}$ which arises in QCD because the masses of the u and d quark m_{d} and m_{u}, themselves, are small compared to Λ_{QCD}.

Due to chiral symmetry, the vector and axial vector currents are separately conserved. The chiral symmetry group can be enlarged to $SU(3)_L \times SU(3)_R$ if also the mass of the s quark is treated as small compared with the QCD scale.

In the case of a light quark q, the complicated equations of motion can be simplified by applying an effective theory where the quark mass is set to zero. This works well as long as the real light-quark mass is small enough in comparison to the QCD scale that it scarcely influences the dynamics of the strong interactions. The small quark mass can be considered as a perturbation and the expansion in the perturbation term m_q/Λ_{QCD} gives corrections on the predictions of the effective theory.

A new symmetry has come into the picture with the discovery of heavy quarks Q. In contrast to the symmetries of the light quarks mentioned above, this symmetry arises when the mass of a quark m_Q is much larger than the scale Λ_{QCD}. A heavy quark is surrounded by a hadronic 'sea' of light quarks and gluons often referred to as the light constituents or light degrees of freedom of the hadronic system, but the heavy quark will hardly notice this. Its motion will fluctuate only slightly about that of a free heavy quark and the heavy quark therefore defines its own centre of mass. On the other hand, the light quarks and gluons around it will not notice anything if the heavy quark is replaced by another sufficiently heavy quark with a different mass.

We can feel this intuitively, but what is the theory behind it? The size of the hadronic system is determined by the hadron radius, $R_{had} \sim \frac{1}{\Lambda_{QCD}} \sim 1$ fm. The exchange of momentum between the heavy and light quarks is of order Λ_{QCD}. The soft gluons exchanged can only probe distances larger than the Compton wavelength λ_Q ($\lambda_Q << R_{had}$). So the quantum numbers of the heavy quark (flavour (mass) and spin) remain hidden for the light quark. For example, the excitation spectra will be the same for any heavy-quark hadron.

The fact that the mass of the heavy quark m_Q is irrelevant can be seen as follows. The hadron and the heavy quark have (approximately) the same velocity, so in the rest frame of the hadron the heavy quark is also at rest. The wave function of the light quark is a solution of the QCD equation of motion with the boundary condition that a static source of colour has been placed at the position of the heavy quark. Since the mass does not enter the boundary condition, also the solutions do not depend on the heavy quark mass[2]. This leads to an $SU(N)$ symmetry, with N the number of heavy quarks.

The fact that the heavy-quark spin is decoupled leads to an $SU(2N)$ symmetry. This means, for instance, that every spectral level consists of a degenerate doublet with total spin $J_\pm = j_q \pm s_Q$, where j_q is the total angular momentum of the light quark and s_Q is the spin of the heavy quark[3]. From the above, it follows that in the limit $m_Q \to \infty$ the configuration of the spectral levels is the same for heavy quarks that only differ in spin or flavour. This provides us with relations between the properties of the heavy mesons and baryons containing a c quark, D, D^*, D^{**} and Λ_c, on the one hand, and the corresponding ones containing a b quark, B,B^*, B^{**} and Λ_b, on the other. Here the single asterisk indicates the excited state with $L = 0$ ($J_+ = 1$) and the double asterisk indicates the orbitally excited states with $L = 1$ ($J_\pm = 0, 1, 2$).

As in the case of the light-quark system mentioned above, one can adopt an effective theory: Heavy Quark Effective Theory (HQET). However, here the quark mass is not set to zero, but it approaches infinity. This effective theory and its implications will be further

[2]The heavy-quark flavour symmetry is analogous to the fact that the different isotopes of the same element have the same chemistry

[3]The spin symmetry is analogous to the fact that the hyperfine levels in atoms are (nearly) degenerate

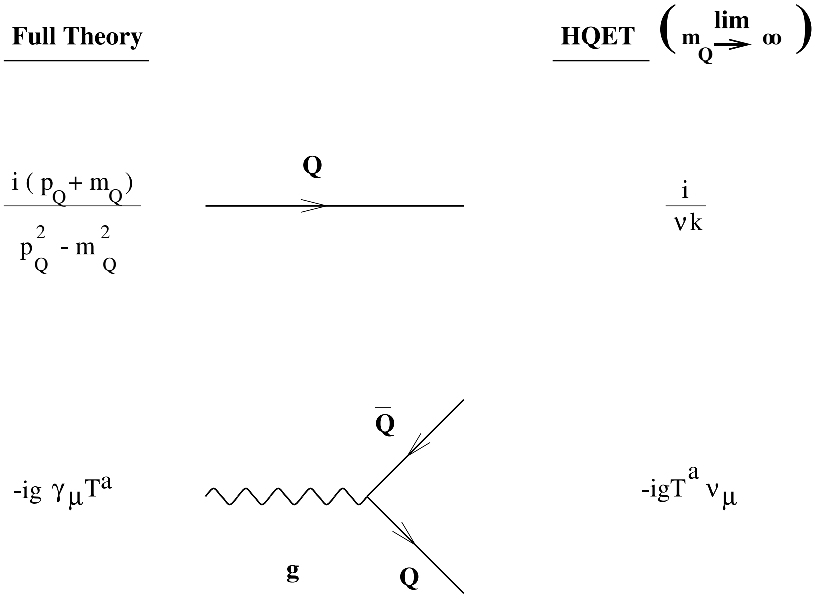

Figure 1.1: *Feynman rules that play a role for heavy quark physics: the quark propagator and the quark-gluon interaction, at the left for the full theory and at the right for HQET.*

discussed in the next section.

One should note that the $SU(2N)$ spin-flavour symmetry of HQET is not manifest in the full theory of QCD. The HQET is a good approximation of QCD in a certain kinematic region and then only for systems in which the heavy quark interacts predominantly by the exchange of soft gluons.

As in the case of chiral symmetry, it is possible for approximate heavy-quark spin-flavour symmetry to treat the perturbation terms in $\Lambda_{\mathrm{QCD}}/m_{\mathrm{Q}}$ as corrections to the predictions based on the effective heavy-quark theory.

1.3 Heavy-Quark Effective Theory (HQET)

The HQET is treated in [1] and several lectures [10, 14–18] in great detail. I will summarise it briefly in this section. The Feynman rules for HQET can be derived in two ways. One can derive them from the Feynman rules of the full theory by taking the quark mass to infinity while keeping the velocity ν^μ fixed. The rules for the full QCD propagator and quark-gluon interaction are given in figure 1.1. The momentum of the heavy quark can be written as: $P^\mu_{\mathrm{Q}} = m_{\mathrm{Q}}\nu^\mu + k^\mu$, with k^μ being a residual momentum small compared to m_{Q}. The propagator in the effective theory is then given by: $\frac{i}{\nu \cdot k}$ and the vertex of the heavy-quark gluon interaction by $-igT^a\nu_\mu$ [1].

The same result can be obtained from that part of the Lagrangian density that describes the heavy-quark field:

$$\mathcal{L} = \bar{Q}(i\not{D} - m_{\mathrm{Q}})Q \tag{1.1}$$

with $Q = e^{-im_Q v\cdot x}h_v^{(Q)}$, where $h_v^{(Q)}$ is the heavy-quark field which satisfies $\not{v}h_v^{(Q)} = h_v^{(Q)}$ and $\not{D} = \gamma^\mu\delta_\mu + igT^aA_\mu^a$. For a quark with velocity v, in the limit $m_Q \to \infty$ the Lagrangian density becomes [1]:

$$\mathcal{L}_\infty = \bar{h}_v^{(Q)} iv \cdot Dh_v^{(Q)}. \tag{1.2}$$

This effective Lagrangian density also reproduces the Feynman rules of the HQET. The equation of motion is then given by: $v \cdot Dh_v^{(Q)} = 0$.

The field $h_v^{(Q)}$ destroys a heavy quark of four-velocity v, but it does not create an antiquark. So, since pair production is not present in the effective theory, the field of the antiquark is an independent degree of freedom. This is a U(1) symmetry of the effective Lagrangian that results in the conservation of the heavy quarks and is not present in the Lagrangian of the full theory.

Since no Dirac matrices appear in the Lagrangian density, interactions of a heavy quark with gluons leave its spin unchanged. Also the mass of the heavy quark is not in the Lagrangian density. So, for N heavy-quark flavours with corresponding fields $h_v^{(j)}$ for the j^{th} heavy quark, the Lagrangian density becomes:

$$\mathcal{L}_\infty = \sum_{j=1}^{N} \bar{h}_v^{(j)} iv \cdot Dh_v^{(j)}. \tag{1.3}$$

This Lagrangian density is invariant under rotations in flavour space. This is an $\mathrm{SU}(2N)$ spin-flavour symmetry.

Only effects that survive in the limit $m_Q \to \infty$ are illustrated here. First order corrections can be expressed in terms of Λ_{QCD}/m_Q. Furthermore, a field $H_v^{(Q)}$ creating a heavy quark of velocity v can be added to the description. This occurs since the heavy quark is not precisely on shell as it propagates. It is approximately on shell, however, so that $H_v^{(Q)}$ is small compared to $h_v^{(Q)}$. The field $H_v^{(Q)}$ can be written in terms of $h_v^{(Q)}$ and the effective Lagrangian density is thus given by [1]:

$$\mathcal{L}_{\text{eff}} = \bar{h}_v^{(Q)} iv \cdot Dh_v^{(Q)} + \frac{\bar{h}_v^{(Q)}}{2m_Q}[(iD)^2 - \frac{1}{2}g\sigma_{\mu\nu}G^{a\mu\nu}T^a]h_v^{(Q)} \tag{1.4}$$

with $G^{a\mu\nu}$ the gluon field strength tensor. The last term describes the coupling of the heavy-quark spin to the gluon field. It is the last term in the above equation that violates the heavy-quark spin symmetry and it is the matrix element of this term that gives rise to the $P_Q^* - P_Q$ mass difference, where P_Q^* and P_Q are of the same degenerate doublet, with P_Q^* being the J_+ state and P_Q the J_- state.

1.4 Examples of HQET in spectroscopy

In spectroscopy, the spin-flavour symmetry leads to relations between the properties of hadrons that contain a heavy quark that differs only in spin or flavour. As described in the previous sections, the dynamics of hadronic states is independent of the spin and mass of the heavy quark and can thus be classified by the quantum numbers (for example the total spin) of the light degrees of freedom. For fixed $j_q \neq 0$, there is a doublet of degenerate states with total spin $J_{\pm} = j_q \pm \frac{1}{2}$.

The mass of a hadron containing a heavy quark Q can be written as:

$$m_H = m_Q + \bar{\Lambda} + \frac{\Delta m^2}{2m_Q} + O(1/m_Q^2), \tag{1.5}$$

where the parameter $\bar{\Lambda}$ arises from the part of the Lagrangian that is independent of the heavy quark mass [19] and the quantity Δm^2 can be parametrised as follows [20] :

$$\Delta m^2 = -\lambda_1 + 2\left[J(J+1) - \frac{3}{2}\right]\lambda_2, \tag{1.6}$$

where J is the total spin of the meson. The first term divided by $2m_Q$ arises from the kinetic energy of the heavy quark inside the meson. The second term describes the interaction of the heavy-quark spin with the gluon field. The hadronic parameters $\bar{\Lambda}$, λ_1 and λ_2 are independent of m_Q.

First, we give an example where HQET provides a accurate prediction with no need for corrections. The theory predicts for the mass splittings between the two members of the spin doublet with $j_q = 1/2$:

$$\begin{aligned} \Delta_B &= m_{B^*}^2 - m_B^2 = 4\lambda_2 + O(1/m_b), \\ \Delta_D &= m_{D^*}^2 - m_D^2 = 4\lambda_2 + O(1/m_c), \end{aligned} \tag{1.7}$$

so that $m_{B^*}^2 - m_B^2 \simeq m_{D^*}^2 - m_D^2$. The values obtained from the data [4] of (0.49 $\pm$ 0.03) GeV^2 and (0.545 $\pm$ 0.003) GeV^2 for Δ_B and Δ_D, respectively, are compatible with this prediction.

On the other hand, the mass splitting between the ground-state mesons and baryons containing a heavy quark serves as an example where corrections can no longer be ignored. The HQET predicts:

$$\begin{aligned} \Delta_b = m_{\Lambda_b} - m_B &= \bar{\Lambda}_{baryon} - \bar{\Lambda}_{meson} + O(1/m_b), \\ \Delta_c = m_{\Lambda_c} - m_D &= \bar{\Lambda}_{baryon} - \bar{\Lambda}_{meson} + O(1/m_c), \end{aligned} \tag{1.8}$$

and that these two mass splittings should be similar. The values obtained from the data [4] of (345 $\pm$ 9) MeV and (415.6 $\pm$ 0.6) MeV for Δ_b and Δ_c, respectively, are not compatible with the theoretical predictions. In this case, sizable corrections are needed by a term $3\lambda_2/2m_Q$ on the right hand side [10]. After this term is included, a value of (311 $\pm$ 9) MeV and (320 $\pm$ 1) MeV is obtained for Δ_b and Δ_c, respectively. So both mass splittings are indeed the same after these corrections .

After introducing the spin-averaged meson masses $\bar{m}_B = \frac{1}{4}(m_B + 3m_{B^*}) \simeq 5.31$ GeV and $\bar{m}_D = \frac{1}{4}(m_D + 3m_{D^*}) \simeq 1.97$ GeV, the difference between the two heavy b and c quarks, can be calculated with the use of equation (1.5):

$$m_b - m_c = (\bar{m}_B - \bar{m}_D)\left\{1 - \frac{\lambda_1}{2\bar{m}_B}\bar{m}_D + O(1/m_Q^3)\right\}, \tag{1.9}$$

where $O(1/m_Q^3)$ is used as a generic notation representing terms suppressed by three powers of the b or c quark masses. A theoretical estimate for the parameter λ_1 is: $\lambda_1 = 0.3 \pm 0.2$ [21–23]. This leads to

$$m_b - m_c = (3.39 \pm 0.03 \pm 0.03)\ \text{GeV}, \tag{1.10}$$

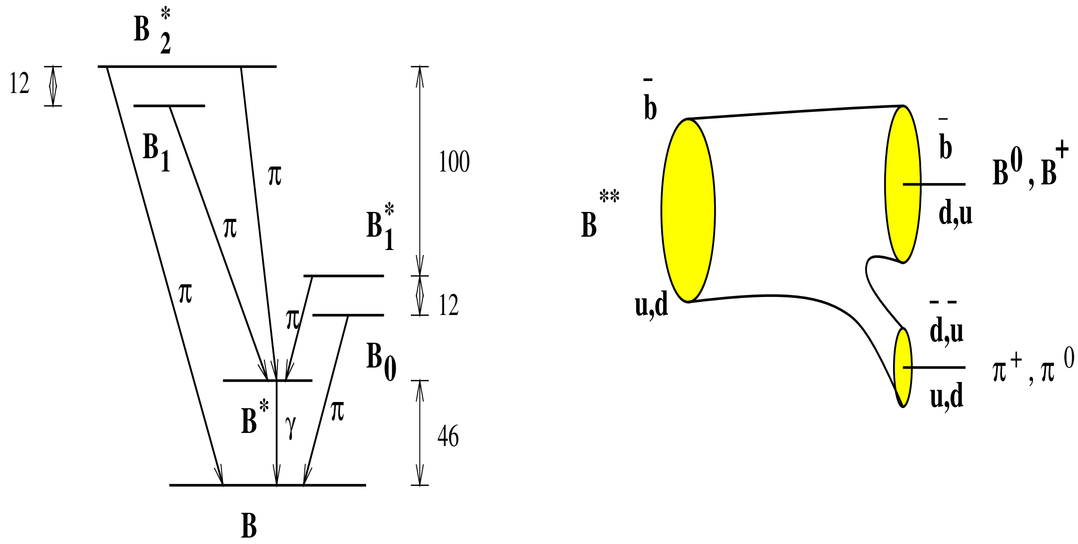

Figure 1.2: *Modes of the decay of B^{**}_{ud} to $B\pi$ and $B^*\pi$, where the mass splittings indicated are given in MeV (a) and the diagram of the corresponding strong interaction (b).*

where the first error is due to the uncertainty in the value of λ_1, and the second one estimates the unknown higher-order corrections. So, although, the separate quark masses are not well known, it is possible to calculate the quark mass difference very accurately with the help of HQET.

1.5 The orbitally excited L=1 beauty states

Identification of the charge of the pion (or kaon) resulting from the strong decay of an excited beauty meson could possibly serve as a tag of the initial flavour of the neutral B meson in CP-violation studies [24]. The statistics of data taken by the LEP experiments, however, is not high enough for such studies. Future experiments at Fermilab and LHC will be able to possibly make these measurements.

This thesis is concerned rather with the study of the spectroscopy of the orbitally excited states, a source of valuable information on the quark model and as a means to distinguish between different theoretical predictions.

1.5.1 Predictions for orbitally excited heavy-quark states and $\mathrm{B}^{**}_{\mathrm{u,d}}$

The flavour symmetry of HQET can be used to make predictions for the excited beauty system from results already obtained in the excited charm and even strange systems. For heavy mesons, the degenerate pairs of states are characterised by the total angular momentum of the light degrees of freedom, $j_{\mathrm{q}} = L \pm \frac{1}{2}$, and each state of a degenerate pair is indicated by the total spin of the meson, $\vec{J} = \vec{j}_{\mathrm{q}} + \vec{s}_{\mathrm{Q}}$. In the case of excited (L=1) heavy mesons these are $j_{\mathrm{q}} = \frac{1}{2}$ (with total spin J=0,1, respectively) and $j_{\mathrm{q}} = \frac{3}{2}$ (with total spin J=1,2, respectively).

The different excited L=1 states in the beauty system are labelled B_0 and B_1^* for the $j_q = \frac{1}{2}$ states and B_1 and B_2^* for $j_q = \frac{3}{2}$, where the state indicated by a asterisk is always the higher lying one of the doublet and the subscript is the total spin of the excited meson (see figure 1.2). $B^{**}_{u,d}$ is the generic name for those four excited states.

The mass of a heavy-light quark meson can be written as [25, 26]:

$$M(L(j_q)) = M(1S) + E(L(j_q)) + \frac{C(L(j_q))}{m_Q}, \tag{1.11}$$

with $M(1S)$ the spin-averaged mass of the ground state as described in the previous section, $E(L(j_q))$ the excitation energy and $C(L(j_q))$ incorporates the higher-order contributions. For the $j_q = \frac{3}{2}$ states, the above equation gives for the excited strange and charmed mesons:

$$K^{**}: \qquad \begin{cases} M(P_2)_K - M(1S)_K = & E(P)_K + \frac{C(P_2)}{m_s} \\ M(P_1)_K - M(1S)_K = & E(P)_K + \frac{C(P_1)}{m_s} \end{cases}$$

$$D^{**}: \qquad \begin{cases} M(P_2)_D - M(1S)_D = & E(P)_D + \frac{C(P_2)}{m_c} \\ M(P_1)_D - M(1S)_D = & E(P)_D + \frac{C(P_1)}{m_c} \end{cases}$$

with $E(P)_D = E(P)_K - \delta$ and $\delta = 32$ MeV [25,26]. Using the experimental results for observed P-wave charm and strange mesons, one can extrapolate to obtain predictions for the P-wave beauty mesons for the $j_q = \frac{3}{2}$ states of 5.767 GeV and 5.755 GeV for the B_2^* and B_1 states, respectively.

Since $P(\frac{1}{2})_D$ mesons have not yet been observed, this method cannot be used (yet) to predict the masses of the $j_q = \frac{1}{2}$ $B^{**}_{u,d}$ states. In reference [27] the mass difference between the two doublets is estimated to be of the order of 100 MeV. The mass splittings predicted between the $B^{**}_{u,d}$ states are indicated in figure 1.2(a) [4].

The decays of $B^{**}_{u,d}$ are given in figure 1.2 (b). Combining chiral and heavy-quark symmetry suggests that $j_q = \frac{1}{2}$ P-wave states should have large widths for pionic decay to the ground states since they can decay via S-waves. Mixing of the narrow $P(\frac{3}{2})$ level with the broader $P(\frac{1}{2})$ state is predicted to be negligible. This is suggested by the fact that the narrow width observed for the D_{s1} is consistent with the prediction from HQET [13]. This should also hold for B_s and B. The B_2^* and B_1 states can only decay via a D-wave and are therefore narrow. The predicted width for $B^{**} \to B^{(*)}\pi$ is 11 MeV for the B_2^* state to $B^*\pi$, 11 MeV for the B_2^* state to $B\pi$ and 17 MeV for the B_1^* state to $B^*\pi$. The total decay width amounts to 25 MeV for the $J^P = 2^+$ state and 21 MeV for the 1^+ state [25].

The relative production rates of the four $B^{**}_{u,d}$ states are not predicted by HQET, but a reasonable assumption is spin counting , $2J+1$ with J the total spin of the heavy hadron. This method results in the ratio 5:3:3:1 for $B_2^* : B_1 : B_1^* : B_0$. The measured production ratio $\frac{BR(b \to B^*)}{BR(b \to B^{(*)})}$ of about 0.75 supports this assumption.

[4] There are recent theoretical predictions [28, 29] that argue that the $j_q = 1/2$ multiplet should lie above the $j_q = 3/2$ multiplet due to mass and relativistic corrections. Unfortunately, at present no experimental results exist that can single out one of these different alternatives.

1.5.2 Experimental results on the $B^{**}_{u,d}$ meson

Evidence of P-wave charm mesons has been found by CLEO [30, 31] and ARGUS [32–34] and more recently DELPHI [35] and ALEPH [36] have shown their results. From consistency arguments, it was expected that resonances like those in the D system would also exist in the beauty system. DELPHI [37] and OPAL [38], and later ALEPH [39, 40], have shown that a resonance does indeed occur in the charged-pion channel, although broader than expected. The experimental results of the three LEP experiments are summarised in table 1.1. The most recent result from ALEPH [40] is obtained by using fully reconstructed B decays. In that paper the mass of the B^*_2 resonance state is obtained by performing a fit to the mass spectrum which fixes the mass differences, widths and relative rates of all spin states according to one particular model. The masses of all other states can be calculated via their mass splittings.

With the installation of the L3 Silicon Microvertex Detector and subsequently better impact parameter resolution and enhanced b-tagging capability, an analysis of $B^{**}_{u,d}$ has also become possible in L3. Firstly, the charged-pion decay of the $B^{**}_{u,d}$ is analysed. The L3 detector, which has a high resolution electromagnetic calorimeter, allows in addition for the first time the analysis of the neutral-pion decay channel. This provides the important check of the assumed isospin symmetry.

experiment	$\overline{M}$(GeV)	$M_{B^*_2}$ (GeV)	Γ(MeV)	Br (%)	σ(MeV)	$N_{B^{**}_{u,d}}$
DELPHI [37]	5.732 ± 0.005 ± 0.020		145 ± 28	27 ± 6 ± 6	79 ± 8 ± 8	2157 ± 120 ± 323
OPAL [38]	5.681 ± 0.011		116 ± 24	18 ± 4		738 ± 121
ALEPH [39]	5.703 ± 0.004 ± 0.010			27.9 ± 1.6 ± 5.9	53 ± 3 ± 9	1944 ± 108 ± 161
ALEPH [40]		5.739 +8 -11 +6 -4		31 ± 9 +6 -5		
CDF [41]	5.71 ± 0.02			28 ± 0.06 ± 0.03		

Table 1.1: *Experimental results on $B^{**}_{u,d}$. $\overline{M}$ is the average $B^{**}_{u,d}$ mass, $M_{B^*_2}$ is the mass of the B^*_2 orbitally excited state, Γ the Breit-Wigner width of the signal, Br the production rate, σ the Gaussian width of the signal and $N_{B^{**}_{u,d}}$ the number of $B^{**}_{u,d}$ in the signal*

1.5.3 Experimental results on the B^* meson

The B^* is the well-established vector partner of the pseudoscalar $\mathrm{B_{ud}}$. Due to the small mass difference all strong decays of B^* are forbidden, implying a branching ratio for the electromagnetic $\mathrm{B}^* \rightarrow \mathrm{B}\gamma$ decay close to 100 %. The relative production rate, $N_{\mathrm{B}^*}/(N_{\mathrm{B}^*}+N_{\mathrm{B}})$, is a measurement of: $V/(V+P)$, the fraction of vector meson production to the sum of vector and pseudoscalar production. Spin counting predicts: $V/(V+P) \sim 0.75$. The production and decay of orbitally excited B mesons ($\mathrm{B}^{**}_{\mathrm{u,d}}$) to B or B^* mesons may modify the measurements somewhat. Also phase-space effects arising from the mass difference between the vector and pseudoscalar states can alter the prediction. In the charm sector a value much lower than 0.75 of about 0.5 [42] is found. This low value is not well understood. The experimental results for the B^* signal are summarised in table 1.2.

experiment	Br (%)	Q(MeV)	N_{B^*}
CUSB [43]	- - -	45.4 ± 1.0 -	- - -
CLEO [44]	- - -	46.2 ± 0.3 ± 0.8	- - -
DELPHI [45]	72 ± 3 ± 6	45.5 ± 0.3 ± 0.8	3009 ± 108 ± 65
OPAL [46]	76.0 ± 3.6 ± 8.3	46.2 ± 0.3 ± 0.8	1894 ± 89 -
ALEPH [47]	77.1 ± 2.6 ± 7.0	45.30 ± 0.35 ± 0.87	4227 ± 140 ± 252
L3 [48, 49]	76 ± 4 ± 6	46.3 ± 1.9 -	1378 ± 145 -

Table 1.2: *Experimental results on* B^*. *Br is the production rate, Q is the* $\mathrm{B}^* - B$ *mass difference and* N_{B^*} *is the number of* B^* *in the signal.*