Heavy Flavour Decays - Introduction and Summary

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Abstract: We review some selected topics in the decays of heavy flavours, beauty and charm, which are of principal interest at HERA-B and HERA. The topics in B physics include: an update on the quark mixing matrix and CP violating phases, issues bearing on an improved resolution on the CP-violating phase $\Delta(\sin 2\beta)$, prospects of measuring radiative and semileptonic rare B decays, the B_s^0 - $\overline{B_s^0}$ mixing ratio x_s, improved measurements of the B_d^0 - $\overline{B_d^0}$ mixing ratio x_d and the B-hadron lifetimes, in particular $\tau(\Lambda_b)$. In the charm sector, we have focussed on rare decays and D^0- $\overline{D^0}$ mixing, whose measurements will signal physics beyond the standard model.

1 Introduction

The origin of CP violation, even 32 years after its discovery by Christenson et al. in neutral K decays [1], remains a puzzle. So far the ratio ϵ_K is the only precisely determined CP violating quantity in particle physics [2]. In the standard model (SM), the couplings of the charged vector bosons $W^{\pm}$ with the quark-antiquark pairs are complex, which for three generations lead to a complex phase in the quark mixing matrix - the Cabibbo-Kobayashi-Maskawa (CKM) matrix [3]. The quantity ϵ_K in the SM measures essentially this complex phase. However, this hypothesis remains to be tested by independent measurements of other CP-violating quantities. In neutral B-meson decays, the angles in the CKM-unitarity triangle shown in Fig. 1 are characteristic measures of CP violation, as the CP violating asymmetries in the decay rates of a B-hadron into specific modes and their CP-conjugates can be related to these angles. The primary aim of the HERA-B experiment is to measure the CP-violating asymmetry in B decays related to the phase $\sin(2\beta)$.

A related and equally important goal of the HERA-B physics programme is to quantitatively test the unitarity of the CKM matrix, in which apart from the improved measurements of the matrix elements $|V_{cb}|$ and $|V_{ub}|$, the matrix element $|V_{td}|$ plays a central role (see Fig. 1). This matrix element can, in principle, be determined in a number of B and K decays [4, 5]. At HERA-B, this would require either measuring the mass difference between the two eigenstates of the B_s^0-$\overline{B_s^0}$ system, ΔM_s, (equivalently the ratio of the mass difference to the averaged decay width $x_s = \Delta M_s/\Gamma_s$), which can then be compared with the already well-measured quantity

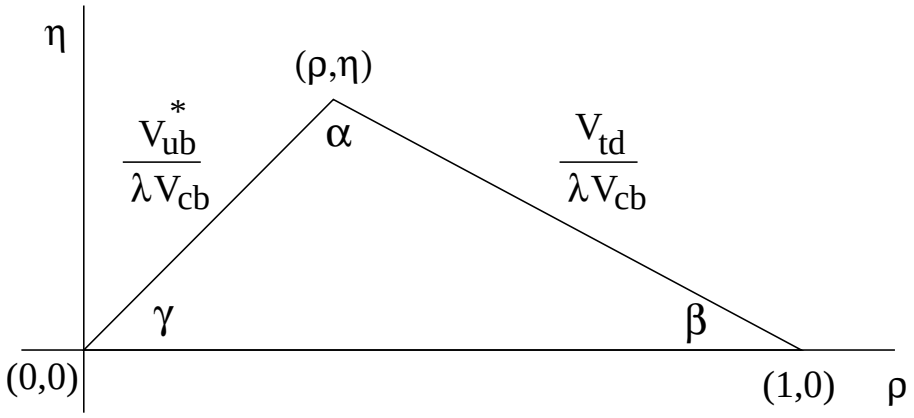

Figure 1: The unitarity triangle. The angles α, β and γ can be measured via CP violation in the B system.

ΔM_d [6] to extract the ratio $|V_{td}|/|V_{ts}|$, or the branching ratios of at least one of the CKM-suppressed rare decays, such as $B^0 \to \rho^0 + \gamma$, which would yield $|V_{td}|/|V_{cb}|$. These measurements are also very challenging; apart from efficient triggers and good vertex resolution, both high luminosity and higher proton beam energy will be big assets here. The unitarity of the CKM matrix will, of course, be very precisely tested by the measurements of all three angles in the unitarity triangle shown in Fig. 1. This, however, is an ambitious programme, which may or may not materialize in three years of HERA-B running and may require a post-HERA-B facility such as the LHC. Hence, in this workshop, we have concentrated on $\sin(2\beta)$, x_s, and rare B decays.

Concerning charm physics at HERA and HERA-B, which will undoubtedly contribute to our understanding of the dynamics of heavy flavour production in QCD (reviewed here by Eichler and Frixione [7]), the principal interest is in attaining improved experimental sensitivities in searches for rare decays, D^0 - $\overline{D^0}$ mixing and CP violation. As opposed to the FCNC phenomena in B decays, SM predicts tiny FCNC decay rates, mixing frequency, and CP asymmetries in the charm sector. This reflects the observed pattern of quark masses and mixings and the built-in GIM-mechanism [8] in the SM. Long-distance (LD) effects may increase some of the transition rates but these enhancements in all realistic estimates remain modest; FCNC-related phenomena in the charm sector remain unmeasurable in SM for all practical purposes. Hence, finding a positive signal in any of the rare decays such as $D^0 \to \ell^+\ell^-$, $D^0 \to \gamma\gamma$, D^0 - $\overline{D^0}$ mixing or CP violation in any charmed hadron decay mode will unambiguously signal physics beyond the SM. As argued quantitatively in these proceedings by Grab [9] and Tsipolitis [10], counting rate is the decisive parameter in such searches and an increase in HERA-luminosity will be very welcome in the *ep* mode. At HERA-B, the anticipated charmed hadron production rate is already very high. Here, one has to develop an efficient trigger to make use of this high yield and do competitive physics.

2 Flavour Mixings and CP Violation in the SM and at HERA-B

The profile of the CKM matrix [3] is updated by Ali and London in [11]. In particular, they focussed on the CKM unitarity triangle and CP asymmetries in B decays, which are the principal objects of interest in experiments at present and forthcoming B facilities, in particular HERA-B.

2.1 Present profile of the CKM unitarity triangle

In updating the CKM matrix elements the Wolfenstein parametrization [12] has been used which follows from the observation that the elements of this matrix exhibit a hierarchy in terms of λ, the Cabibbo angle. In this parametrization the CKM matrix can be written approximately as

$$V_{CKM} \simeq \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda(1+iA^2\lambda^4\eta) & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} . \tag{1}$$

The allowed region in ρ-η space can be displayed quite elegantly using the so-called unitarity triangle. The unitarity of the CKM matrix leads to the following relation:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \ . \tag{2}$$

Using the form of the CKM matrix in Eq. 1, this can be recast as

$$\frac{V_{ub}^*}{\lambda V_{cb}} + \frac{V_{td}}{\lambda V_{cb}} = 1 \ , \tag{3}$$

which is a triangle relation in the complex plane (i.e. ρ-η space), illustrated in Fig. 1. Thus, allowed values of ρ and η translate into allowed shapes of the unitarity triangle.

The present status of the CKM-Wolfenstein parameters λ and A is as follows [2, 6]:

$$\begin{aligned} |V_{us}| &= \lambda = 0.2205 \pm 0.0018 \ , \\ |V_{cb}| &= 0.0393 \pm 0.0028 \implies A = 0.81 \pm 0.058 \ , \end{aligned} \tag{4}$$

The other two parameters ρ and η (the all important complex phase) are determined at present through the measurements of $|V_{ub}|/|V_{cb}|$, ΔM_d, the B_d^0-$\overline{B_d^0}$-mixing induced mass difference, and $|\epsilon_K|$, the CP-violating parameter in K decays. The present experimental input can be summarized as [11]:

$$\begin{aligned} \sqrt{\rho^2+\eta^2} &= 0.363 \pm 0.073 \quad (\text{from } |V_{ub}/V_{cb}| = 0.08 \pm 20\%), \\ (f_{B_d}\sqrt{\hat{B}_{B_d}}/1 \text{ GeV})\sqrt{(1-\rho)^2+\eta^2} &= 0.202 \pm 0.017 \quad (\text{from } \Delta M_d = 0.464 \pm 0.018 \ (ps)^{-1}), \\ \hat{B}_K\eta[0.93 + (2.08 \pm 0.34)(1-\rho)] &= (0.79 \pm 0.11) \quad (\text{from } |\epsilon_K| = (2.280 \pm 0.013) \times 10^{-3}) \end{aligned} \tag{5}$$

The errors of the last two lines include the small experimental errors on ΔM_d (3.9%) and $|\epsilon_K|$ (0.6%), as well as the larger errors on m_t^2 (11%) and A^2 (14%). In [11], two types of CKM fits have been considered.

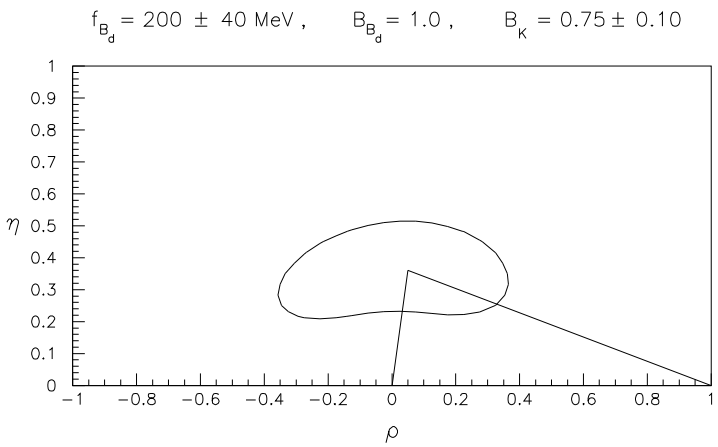

Figure 2: Allowed region in ρ-η space, from a simultaneous fit to both the experimental and theoretical quantities given in eqs. (4) and (5). The theoretical errors are treated as Gaussian for this fit. The solid line represents the region with $\chi^2 = \chi^2_{min} + 6$ corresponding to the 95% C.L. region. The triangle shows the best fit. (From [11].)

- Fit 1: the "experimental fit." Here, only the experimentally measured numbers are used as inputs to the fit with Gaussian errors; the coupling constants $f_{B_d}\sqrt{\hat{B}_{B_d}}$ and $\hat{B}_K$ are given fixed values.
- Fit 2: the "combined fit." Here, both the experimental and theoretical numbers (indicated on Fig. 2) are used as inputs assuming Gaussian errors for the theoretical quantities.

These two methods provide very similar results and we focus here on the "combined fit" (Fit 2), which is shown in terms of the allowed CKM triangle in Fig. 2. As is clear from this figure, the allowed region is still rather large at present. However, present data and theory do restrict the parameters ρ and η to lie in the following range:

$$\begin{aligned} 0.20 &\leq \eta \leq 0.52, \\ -0.35 &\leq \rho \leq 0.35 \ . \end{aligned} \tag{6}$$

The preferred values obtained from the "combined fit" are

$$(\rho, \eta) = (0.05, 0.36) \quad (\text{with } \chi^2 = 6.6 \times 10^{-3}) \ , \tag{7}$$

which gives rise to an almost right-angled unitarity triangle, with the angle γ being close to 90 degrees.

2.2 CP Violation in the B System

It is expected in the SM that the B system will exhibit large CP-violating effects, characterized by nonzero values of the angles α, β and γ in the unitarity triangle (Fig. 1). The most promising method to measure CP violation is to look for an asymmetry between $\Gamma(B^0 \to f)$ and

$\Gamma(\overline{B^0} \to f)$, where f is a CP eigenstate. If only one weak amplitude contributes to the decay, the CKM phases can be extracted cleanly (i.e. with no hadronic uncertainties). Thus, $\sin 2\alpha$, $\sin 2\beta$ and $\sin 2\gamma$ can in principle be measured in $\overline{(B^0)} \to \pi^+\pi^-$, $\overline{(B^0)} \to J/\psi K_s$ and $\overline{(B_s)} \to \rho K_s$, respectively. Penguin diagrams will, in general, introduce some hadronic uncertainty into an otherwise clean measurement of the CKM phases. In the case of $\overline{(B^0)} \to J/\psi K_s$, the penguins do not cause any problems, since the weak phase of the penguin is the same as that of the tree contribution. Thus, the CP asymmetry in this decay still measures $\sin 2\beta$. This augers well as measuring this asymmetry is the primary goal of the HERA-B experiment.

For $\overline{(B^0)} \to \pi^+\pi^-$, however, although the penguin is expected to be small with respect to the tree diagram, it will still introduce a theoretical uncertainty into the extraction of α. This uncertainty can, in principle, be removed by the use of an isospin analysis, which requires the measurement of the rates for $B^+ \to \pi^+\pi^0$, $B^0 \to \pi^+\pi^-$ and $B^0 \to \pi^0\pi^0$, as well as their CP-conjugate counterparts. Help will come here from e^+e^- experiments which are the only ones which can measure the $B^0 \to \pi^0\pi^0$ mode. Still, this isospin program is ambitious experimentally. If it cannot be carried out, the error induced on $\sin 2\alpha$ is of order $|P/T|$, where P (T) represents the penguin (tree) diagram. The ratio $|P/T|$ is difficult to estimate since it is dominated by hadronic physics. It is $\overline{(B_s)} \to \rho K_S$ which is most affected by penguins. In fact, the penguin contribution is probably larger in this process than the tree contribution. Other methods to measure γ have been devised, not involving CP-eigenstate final states, and are reviewed in [11].

The CP-violating asymmetries, parametrized by $\sin 2\alpha$, $\sin 2\beta$ and and $\sin^2\gamma$, can be expressed straightforwardly in terms of the CKM parameters ρ and η. The 95% C.L. constraints on ρ and η found previously can be used to predict the ranges of $\sin 2\alpha$, $\sin 2\beta$ and $\sin^2\gamma$ allowed in the standard model. The ranges for the CP-violating rate asymmetries are determined at 95% C.L. to be [11]:

$$\begin{aligned} -0.90 \le \sin 2\alpha \le 1.0 \ , \\ 0.32 \le \sin 2\beta \le 0.94 \ , \\ 0.34 \le \sin^2\gamma \le 1.0 \ . \end{aligned} \tag{8}$$

It is assumed that the angle β is measured in $\overline{(B^0)} \to J/\psi K_s$, and an extra minus sign due to the CP of the final state has been included. Since the CP asymmetries all depend on ρ and η, these ranges for $\sin 2\alpha$, $\sin 2\beta$ and $\sin^2\gamma$ are correlated. The correlation in ($\sin 2\alpha$ - $\sin 2\beta$) is shown in Fig. 3. Finally, in the SM the relation $\alpha + \beta + \gamma = \pi$ is satisfied. However, note that the allowed range for β is rather small. Thus, there is a strong correlation between α and γ [11].

It is seen from this figure that the smallest value of $\sin 2\beta$ occurs in a small region of parameter space around $\sin 2\alpha \simeq 0.8$-0.9. Excluding this small tail, one expects the integrated CP-asymmetry in $\overline{(B^0)} \to J/\psi K_S$ to be at least 20% (i.e., $\sin 2\beta > 0.4$), with the central value estimated as $A(J/\psi K_s) = (30 \pm 7)\%$ [11]. Less satisfactory at present is the prediction for the asymmetry related to $\sin 2\alpha$, for which practically all values are allowed by the fits, including the one $\sin 2\alpha = 0$. If the preferred solution of nature is in the vicinity of $\sin(2\alpha) = 0$, it is improbable that the asymmetry related to this quantity will ever be measured. However, even

if $\sin(2\alpha)$ is not measured at HERA-B, a measurement of $\sin(2\beta)$ and a demonstration that $\sin(2\alpha) \ll \sin(2\beta)$ will lead to non-trivial constraints on the unitarity triangle. Such a scenario will also rule out the so-called superweak theory of CP violation [13], in which case one has the relation $\sin(2\alpha) = \sin(2\beta)$.

Returning to the CP-asymmetry in the decay $\overset{(-)}{B^0} \to J/\psi K_s$, we recall that the time dependent asymmetry is given by

$$\frac{n(t) - \overline{n}(t)}{n(t) + \overline{n}(t)} = D \sin 2\beta \sin xt \,,$$

where $n(t)$ and $\overline{n}(t)$ are the time dependent rates for the decay of a B^0 ($\overline{B}^0$) to decay into $J/\psi K_s$. D is a dilution factor which accounts for imperfect tagging.

The accuracy on $\sin 2\beta$ is given by

$$\Delta \sin 2\beta \propto \frac{1}{P} \frac{1}{\sqrt{N_{B^0}}}$$

where $P = D\sqrt{\epsilon_{tag}}$ is the tagging power, ϵ_{tag} the efficiency to get a tag of the B^0 meson and N_{B^0} the number of reconstructed B^0 mesons. A potential enlargement in the CP reach of HERA-B could be achieved by an increase in the proton energy at HERA and thus an increase in the rate of produced B^0 mesons. This scenario, which would substantially improve the Signal/Background ratio for B physics at HERA-B, is, however, somewhat unlikely. A reduction of the error on $\sin 2\beta$ could however come from reconstructing other B^0 decays which also measure $\sin 2\beta$. This was studied at this workshop for the decays $\overset{(-)}{B^0} \to \chi_c K^0$ by Misuk and Belyaev and for $\overset{(-)}{B^0} \to J/\psi K^{*0}$ by Barsuk [14]. These studies showed that one could expect a gain in statistics of about 20% including both these decays and the favourite mode $B \to J/\psi K_s$.

An increase in the tagging power P and thus a smaller error on $\sin 2\beta$ could also come from new tagging techniques. For this purpose the decay $B^{**+} \to \pi^+ B^0$ was studied by Kagan and Shepherd-Themistocleous in the HERA-B environment [15]. This tagging is particularly useful because it is not spoiled by $B\overline{B}$ mixing. The analysis gave promising results with a tagging power of $P = 0.21$ compared to the tagging with primary leptons which yielded $P = 0.17$. Misuk investigated the possibility to tag the flavour of the B mesons by using cascade leptons from the decay chain $B \to D \to \ell^{\pm}$ and obtained for this tagging method a tagging power of $P = 0.08$ [16]. In summary, these studies undertaken to increase the sensitivity of the HERA-B experiment for $\sin 2\beta$ showed that a gain in the statistical power of about 30% is possible.

2.3 ΔM_s (and x_s) and the Unitarity Triangle

Mixing in the B_s^0-$\overline{B_s^0}$ system is quite similar to that in the B_d^0-$\overline{B_d^0}$ system in the SM in which the B_s^0-$\overline{B_s^0}$ and B_d^0-$\overline{B_d^0}$ box diagrams are dominated by t-quark exchange. Using the fact that $|V_{cb}| = |V_{ts}|$ (Eq. 1), it is clear that one of the sides of the unitarity triangle, $|V_{td}/\lambda V_{cb}|$, can be obtained from the ratio of ΔM_d and ΔM_s,

$$\frac{\Delta M_s}{\Delta M_d} = \frac{\hat{\eta}_{B_s} M_{B_s} \left(f_{B_s}^2 \hat{B}_{B_s} \right)}{\hat{\eta}_{B_d} M_{B_d} \left(f_{B_d}^2 \hat{B}_{B_d} \right)} \left| \frac{V_{ts}}{V_{td}} \right|^2 . \qquad (9)$$

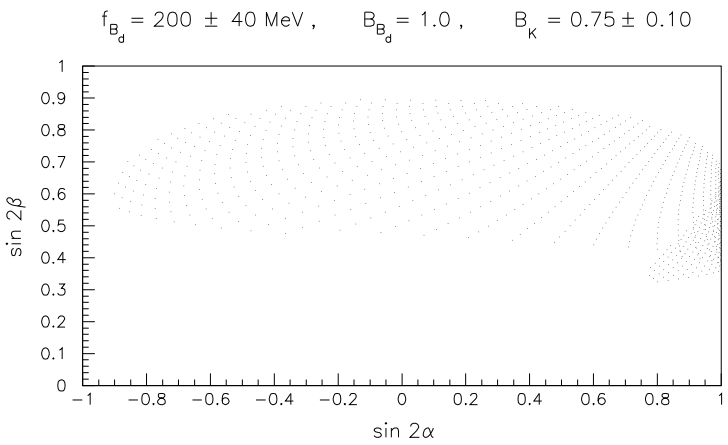

Figure 3: Allowed region of the CP-violating quantities $\sin 2\alpha$ and $\sin 2\beta$ resulting from the "combined fit" of the data for the ranges for $f_{B_d}\sqrt{\hat{B}_{B_d}}$ and $\hat{B}_K$ given in the text. (From [11].)

Here $\hat{\eta}_{B_s} = \hat{\eta}_{B_d} = 0.55$ is the perturbative QCD correction factor [17]. The only real uncertainty (apart from the CKM matrix element ratio which we would like to determine) is the ratio of hadronic matrix elements $f^2_{B_s}\hat{B}_{B_s}/f^2_{B_d}\hat{B}_{B_d}$. Using the determination of A given earlier, $\tau(B_s) = 1.52 \pm 0.07$ ps, and $\overline{m_t} = 165 \pm 9$ GeV, one gets

$$\begin{aligned} \Delta M_s &= (12.8 \pm 2.1)\,\frac{f^2_{B_s}\hat{B}_{B_s}}{(230\ \mathrm{MeV})^2}\ (ps)^{-1}\ , \\ x_s &= (19.5 \pm 3.3)\,\frac{f^2_{B_s}\hat{B}_{B_s}}{(230\ \mathrm{MeV})^2}\ . \end{aligned} \tag{10}$$

The choice $f_{B_s}\sqrt{\hat{B}_{B_s}} = 230$ MeV corresponds to the central value given by the lattice-QCD estimates, and with this the fits in [11] give $x_s \simeq 20$ as the preferred value in the SM. Allowing the coefficient to vary by $\pm 2\sigma$, and taking the central value for $f_{B_s}\sqrt{\hat{B}_{B_s}}$, this gives

$$\begin{aligned} 12.9 &\leq x_s \leq 26.1\ , \\ 8.6\ (ps)^{-1} &\leq \Delta M_s \leq 17.0\ (ps)^{-1}\ . \end{aligned} \tag{11}$$

It is difficult to ascribe a confidence level to this range due to the dependence on the unknown coupling constant factor. All one can say is that the standard model predicts large values for ΔM_s (and hence x_s). The present experimental limit from the combined fit of the ALEPH [18] and OPAL experiments $\Delta M_s > 9.2\ (ps)^{-1}$ [6] is better than the lower bound on this quantity obtained from the CKM fits given above. In particular, the LEP-bound, expressed as $\Delta M_s/\Delta M_d > 19.0$, removes the (otherwise allowed) large-negative-ρ region, leaving the reduced parameter space ($-0.25 \leq \rho \leq 0.35$, $0.25 \leq \eta \leq 0.52$) as the presently allowed one [11]. In terms of the ratio $|V_{td}|/|V_{ts}|$, this implies $|V_{td}|/|V_{ts}| < 0.29$, to be compared with the central value from the CKM fits $|V_{td}|/|V_{ts}| = 0.24$ [11]. The constraints on the unitarity triangle from ΔM_s will become more pronounced with improved data. With the present HERA-B detector, one expects to reach a sensitivity $x_s \simeq 17$ (or $\Delta M_s \simeq 11\ ps^{-1}$) combining various B_s reconstruction

and tagging techniques and data for three years [19]. This overlaps with the x_s-range expected in the SM, though it is somewhat on the lower side. To completely cover the estimated x_s-range in eq. (11), one must strive to increase the experimental sensitivity to $x_s = 26$.

3 Rare B Decays in the SM and at HERA-B

The FCNC B decay with the largest branching ratio in the SM, $B \to X_s + \gamma$, has been observed by the CLEO collaboration [20] through the measurement of the photon energy spectrum in the high E_γ-region. This was preceded by the observation of the exclusive decay $B \to K^\star + \gamma$ by the same collaboration [21]. The present measurements give [22]: $\mathcal{B}(B \to X_s + \gamma) = (2.32 \pm 0.57 \pm 0.35) \times 10^{-4}$ and $\mathcal{B}(B \to K^\star + \gamma) = (4.2 \pm 0.8 \pm 0.6) \times 10^{-5}$, yielding an exclusive-to-inclusive ratio: $R_{K^*} = \Gamma(B \to K^\star + \gamma)/\Gamma(B \to X_s + \gamma) = (18.1 \pm 6.8)\%$. In the SM the decay rates determine the ratio of the CKM matrix elements $|V_{ts}|/|V_{cb}|$ and the quantity R_{K^*} provides information on the decay form factor in $B \to K^\star + \gamma$. It is important to undertake independent measurements of the above-mentioned decays and related processes elsewhere.

A Monte Carlo study by Saadi-Lüdemann described in these proceedings [23] shows that the large-p_T photons emerging from the decays $B \to K^* + \gamma$ can, in principle, be distinguished from the background events at HERA-B, which range out earlier in p_T. Only slight modifications to the present HERA-B trigger scheme are necessary. This argument also holds for the photons from the inclusive decay $B \to X_s + \gamma$, as the photon p_T-spectrum is rather hard and the additional requirement of a large-p_T charged track accompanying the energetic photon will be fulfilled by these decays. Since b-quark fragments include typically 20% of the time a B_s^0 meson or a b baryon (henceforth generically called Λ_b), the FCNC rare decays of the B_s^0 meson and Λ_b baryon will be new and valuable additions to this field which cannot be studied at e^+e^- threshold machines, optimized to operate at the $\Upsilon(4S)$ resonance. The approximate equality of the inclusive radiative branching ratios for the decays $B^\pm \to X_s^\pm + \gamma$, $B_d^0 \to X_s^0 + \gamma$, $B_s^0 \to X_{(s\bar{s})}^0 + \gamma$ and $\Lambda_b \to (\Lambda + X) + \gamma$ will test the hypothesis that these decays are indeed dominated by short-distance physics. Given conducive triggers, HERA-B has the potential of contributing significantly to the field of rare B decays. Here, we summarize some representative examples which can be studied at HERA-B, given the present and planned triggers and assuming that 10^9 $b\bar{b}$ pairs will be produced in three years of data taking at HERA-B.

3.1 Inclusive decay rates $B \to X_s + \gamma$ and $B \to X_d + \gamma$

The leading contribution to $b \to s + \gamma$ arises at one-loop from the so-called penguin diagrams. With the help of the unitarity of the CKM matrix, the decay matrix element in the lowest order can be written as:

$$\mathcal{M}(b \to s\ +\gamma) = \frac{G_F}{\sqrt{2}} \frac{e}{2\pi^2} \lambda_t \left(F_2(x_t) - F_2(x_c)\right) q^\mu \epsilon^\nu \bar{s} \sigma_{\mu\nu} (m_b R\ +\ m_s L) b\ . \qquad (12)$$

where $x_i = m_i^2/m_W^2$, and q_μ and ϵ_μ are, respectively, the photon four-momentum and polarization vector, and $\lambda_t = V_{tb} V_{ts}^*$. The (modified) Inami-Lim function $F_2(x_i)$ derived from the

(1-loop) penguin diagrams [24] can be seen in [4]. The measurement of the branching ratio for $B \to X_s + \gamma$ can be readily interpreted in terms of the CKM-matrix element product $\lambda_t/|V_{cb}|$ or equivalently $|V_{ts}|/|V_{cb}|$. For a quantitative determination of $|V_{ts}|/|V_{cb}|$, however, QCD radiative corrections have to be included and the contribution of the so-called long-distance effects estimated. This has been reviewed in [4], yielding:

$$\mathcal{B}(B \to X_s + \gamma) = (3.20 \pm 0.58) \times 10^{-4}, \tag{13}$$

which is compatible with the present measurement $\mathcal{B}(B \to X_s + \gamma) = (2.32 \pm 0.67) \times 10^{-4}$ [20]. Expressed in terms of the CKM matrix element ratio, one gets [4]

$$\frac{|V_{ts}|}{|V_{cb}|} = 0.85 \pm 0.12(\text{expt}) \pm 0.10(\text{th}), \tag{14}$$

which is within errors consistent with unity, as expected from the unitarity of the CKM matrix.

Since the masses and lifetimes of the $B^{\pm}$, B_d^0, and B_s^0 mesons are very similar, the branching ratio quoted above holds (within minor differences) for all three B mesons. The branching ratio for the Λ_b-baryon will be reduced by the ratio of the lifetimes. One estimates,

$$\begin{aligned} \mathcal{B}(\Lambda_b \to (\Lambda + X)\gamma) &= \mathcal{B}(B_d \to X_s\gamma) \left[\frac{\tau(B_d)}{\tau(\Lambda_b)}\right] \\ &= (2.5 \pm 0.6) \times 10^{-4} \ , \end{aligned} \tag{15}$$

where we have used $\tau(B_d)/\tau(\Lambda_b) = 0.78 \pm 0.04$ [25].

The theoretical interest in studying the (CKM-suppressed) inclusive radiative decays $B \to X_d + \gamma$ lies in the first place in the possibility of determining the parameters of the CKM matrix. With that goal in view, one of the relevant quantities in the decays $B \to X_d + \gamma$ is the end-point photon energy spectrum which has to be measured requiring that the hadronic system X_d recoiling against the photon does not contain strange hadrons, so as to suppress the large-E_γ photons from the decay $B \to X_s + \gamma$. This requires, in particular, a good K/π-separation. Assuming that this is feasible, one can determine from the ratio of the decay rates $\mathcal{B}(B \to X_d + \gamma)/\mathcal{B}(B \to X_s + \gamma)$ the CKM-Wolfenstein parameters ρ and η. To get an estimate of the inclusive branching ratio at present, the CKM parameters ρ and η have to be constrained from the unitarity fits discussed above. Taking the preferred values of the fitted CKM parameters from eq. (7), one gets [26, 27]

$$\mathcal{B}(B \to X_d + \gamma) = 1.63 \times 10^{-5}, \tag{16}$$

whereas $\mathcal{B}(B \to X_d + \gamma) = 8.0 \times 10^{-6}$ and 2.8×10^{-5} for the other two extremes $\rho = 0.35$, $\eta = 0.50$ and $\rho = -\eta = -0.25$, respectively. Therefore, one expects $O(10^4)$ $B \to X_d + \gamma$ events at HERA-B, which taking into account an estimated trigger and reconstruction efficiency of 1% would yield $O(10^2)$ reconstructed B decays of this kind. However, one will have to suppress the background from the dominant $B \to X_s + \gamma$ decays which requires further study.

3.2 $\mathcal{B}(B \to V + \gamma)$ and constraints on the CKM parameters

Exclusive radiative B decays $B \to V + \gamma$, with $V = K^*, \rho, \omega$, are also potentially very interesting from the point of view of determining the CKM parameters [29]. The extraction of these parameters would, however, involve a trustworthy estimate of the SD- and LD-contributions in the decay amplitudes.

The SD-contribution in the exclusive decays $(B^\pm, B^0) \to (K^{*\pm}, K^{*0}) + \gamma$, $(B^\pm, B^0) \to (\rho^\pm, \rho^0) + \gamma$, $B^0 \to \omega + \gamma$ and the corresponding B_s decays, $B_s \to \phi + \gamma$, and $B_s \to K^{*0} + \gamma$, involve the magnetic moment operators [4]. The transition form factors governing these decays can be generically defined as:

$$\langle V, \lambda | \frac{1}{2} \bar{\psi} \sigma_{\mu\nu} q^\nu b | B \rangle = i \epsilon_{\mu\nu\rho\sigma} e_\nu^{(\lambda)} p_B^\rho p_V^\sigma F_S^{B \to V}(0). \tag{17}$$

Here V is a vector meson with the polarization vector $e^{(\lambda)}$, $V = \rho, \omega, K^*$ or ϕ; B is a generic B-meson $B^\pm, B^0$ or B_s, and ψ stands for the field of a light u, d or s quark. The vectors p_B, p_V and $q = p_B - p_V$ correspond to the 4-momenta of the initial B-meson and the outgoing vector meson and photon, respectively. Keeping only the SD-contribution leads to obvious relations among the exclusive decay rates,

$$\frac{\Gamma((B^\pm, B^0) \to (\rho^\pm, \rho^0) + \gamma)}{\Gamma((B^\pm, B^0) \to (K^{*\pm}, K^{*0}) + \gamma)} \simeq \kappa_{u,d} \left[\frac{|V_{td}|}{|V_{ts}|} \right]^2 , \tag{18}$$

where $\kappa_i \equiv [F_S(B_i \to \rho\gamma)/F_S(B_i \to K^*\gamma)]^2 \Phi_{u,d}$ and $\Phi_{u,d}$ is a phase-space factor which in all cases is close to 1. Likewise, using the SD-contribution and isospin symmetry yields

$$\Gamma(B^\pm \to \rho^\pm \gamma) = 2\ \Gamma(B^0 \to \rho^0 \gamma) = 2\ \Gamma(B^0 \to \omega\gamma)\ . \tag{19}$$

If the SD-amplitudes were the only contributions, the measurements of the CKM-suppressed radiative decays $(B^\pm, B^0) \to (\rho^\pm, \rho^0) + \gamma$, $B^0 \to \omega + \gamma$ and $B_s^0 \to K^{*0} + \gamma$ could be used in conjunction with the decays $(B^\pm, B^0) \to (K^{*\pm}, K^{*0}) + \gamma$ to determine one of the sides of the unitarity triangle. The present experimental upper limits on the CKM ratio $|V_{td}|/|V_{ts}|$ from radiative B decays are indeed based on this assumption. The present limits on some of the decay modes are reviewed in [4], which yield at 90% C.L.[22]:

$$\left| \frac{V_{td}}{V_{ts}} \right| \leq 0.45 - 0.56\ , \tag{20}$$

depending on the models used for the $SU(3)$ breaking effects in the form factors. The estimated range for this ratio is $0.15 \leq |V_{td}|/|V_{ts}| \leq 0.29$, which implies that an improvement of a factor of 3 - 10 in the experimental sensitivity would result in measurements of several CKM-suppressed radiative decay modes.

The possibility of significant LD-contributions in radiative B decays from the light quark intermediate states has been raised in a number of papers. The LD-contributions in $B \to V + \gamma$ are induced by the matrix elements of the four-Fermion operators (see [4] for definitions and references). Their amplitudes necessarily involve other CKM matrix elements and hence the

simple factorization of the decay rates in terms of the CKM factors involving $|V_{td}|$ and $|V_{ts}|$ no longer holds thereby invalidating the relations (18) and (19) given above. The modified relations have been worked out in [30, 31]. Combining the estimates for the LD- and SD-form factors in [31] and [29], respectively, and restricting the Wolfenstein parameters in the range $-0.25 \leq \rho \leq 0.35$ and $0.2 \leq \eta \leq 0.5$, as discussed above, the following estimates for the absolute branching ratios have been given in [4]:

$$\begin{aligned} \mathcal{B}(B^{\pm} \to \rho^{\pm}\gamma) &= (1.5 \pm 1.1) \times 10^{-6} \ , \\ \mathcal{B}(B^0 \to \rho\gamma) &\simeq \mathcal{B}(B^0 \to \omega\gamma) = (0.65 \pm 0.35) \times 10^{-6} \ , \end{aligned} \tag{21}$$

where we have used the experimental value for the branching ratio $\mathcal{B}(B \to K^* + \gamma)$ [21], adding the errors in quadrature. The large error reflects the poor knowledge of the CKM matrix elements and hence experimental determination of these branching ratios will put rather stringent constraints on the Wolfenstein parameters, in particular ρ.

In addition to studying the radiative penguin decays of the $B^{\pm}$ and B^0 mesons discussed above, HERA-B will be in a position to study the corresponding decays of the B_s^0 meson and Λ_b baryon, such as $B_s^0 \to \phi + \gamma$ and $\Lambda_b \to \Lambda + \gamma$, which have not been measured so far. We list below the branching ratios in a number of interesting decay modes calculated in the QCD sum rule approach in [29].

$$\begin{aligned} \mathcal{B}(B_s \to \phi\gamma) &\simeq \mathcal{B}(B_d \to K^*\gamma) = (4.2 \pm 2.0) \times 10^{-5} \ , \\ \frac{\mathcal{B}(B_s \to K^*\gamma)}{\mathcal{B}(B_d \to K^*\gamma)} &\simeq (0.36 \pm 0.14)\frac{|V_{td}|^2}{|V_{ts}|^2} \\ &\Longrightarrow \mathcal{B}(B_s \to K^*\gamma) = (0.75 \pm 0.5) \times 10^{-6} \ . \end{aligned} \tag{22}$$

The branching ratio for the radiative decay $\Lambda_b \to \Lambda\gamma$ can be calculated in terms of the exclusive-to-inclusive function $R_\Lambda \equiv \Gamma(\Lambda_b \to \Lambda + \gamma)/\Gamma(\Lambda_b \to (\Lambda + X) + \gamma)$, analogous to the ratio R_{K^*}, defined for the B meson decays earlier. This would then give:

$$\mathcal{B}(\Lambda_b \to \Lambda\gamma) = R_\Lambda \mathcal{B}(\Lambda_b \to (\Lambda + X)\gamma) = (3.8 \pm 1.5) \times 10^{-5} \ , \tag{23}$$

where we have used the SM estimate $\mathcal{B}(B_d \to X_s\gamma) = (3.2 \pm 0.6) \times 10^{-4}$ [4], assumed $R_\Lambda = R_{K^*}$, with $R_{K^*} = 0.15 \pm 0.05$ [29] and $\tau(B_d)/\tau(\Lambda_b) = 0.78 \pm 0.04$ [25]. We note that a much smaller branching ratio has been calculated in [28]. The CKM-suppressed decay $\Lambda_b^0 \to n + \gamma$ is related to the decay $\Lambda_b^0 \to \Lambda + \gamma$ by the CKM ratio $|V_{td}|/|V_{ts}|^2$ in the $SU(3)$ limit. Using the central value $|V_{td}|/|V_{ts}|^2 = 0.058$, this gives $\mathcal{B}(\Lambda_b \to n + \gamma) = (2.2 \pm 1.0) \times 10^{-6}$. Estimated counting rates for several of the exclusive decay modes in the HERA-B experimental environment are given in these proceedings [23], taking into account the trigger and reconstruction efficiency. They range between $O(10^2)$ for the CKM-allowed decays and $O(10)$ for the CKM-suppressed decays.

3.3 Inclusive rare decays $B \to X_s\ell^+\ell^-$ in the SM

The decays $B \to X_s\ell^+\ell^-$, with $\ell = e, \mu, \tau$, provide a more sensitive search strategy for finding new physics in rare B decays than for example the decay $B \to X_s\gamma$, which constrains the

magnitude of the effective Wilson coefficient of the magnetic moment operator, C_7^{eff}. The sign of C_7^{eff} (which is negative in the SM but in general depends on the underlying physics) is not determined by the measurement of $\mathcal{B}(B \to X_s + \gamma)$ alone. It is known (see for example [32]) that in supersymmetric (SUSY) models, both the negative and positive signs are allowed as one scans over the allowed SUSY parameter space. We recall that the $B \to X_s \ell^+ \ell^-$ amplitude in the standard model (as well as in SUSY and multi-Higgs models) has two additional terms, arising from the two FCNC four-Fermi operators. Calling their coefficients C_9 and C_{10}, it has been argued in [32] that the signs and magnitudes of all three coefficients C_7^{eff}, C_9 and C_{10} can, in principle, be determined from the decays $B \to X_s + \gamma$ and $B \to X_s \ell^+ \ell^-$.

The differential decay rate in the dilepton invariant mass in $B \to X_s \ell^+ \ell^-$ can be expressed in terms of the semileptonic branching ratio $\mathcal{B}_{sl}$,

$$\begin{aligned}\frac{\mathrm{d}\mathcal{B}(\hat{s})}{\mathrm{d}\hat{s}} &= \mathcal{B}_{sl}\frac{\alpha^2}{4\pi^2}\frac{\lambda_t^2}{|V_{cb}|^2}\frac{1}{f(\hat{m}_c)\kappa(\hat{m}_c)}u(\hat{s})\Big[\left(|C_9^{\mathit{eff}}(\hat{s})|^2 + C_{10}^2\right)\alpha_1(\hat{s},\hat{m}_s) \\ &\quad + \frac{4}{\hat{s}}(C_7^{eff})^2\alpha_2(\hat{s},\hat{m}_s) + 12\alpha_3(\hat{s},\hat{m}_s)C_7^{eff}\Re(C_9^{\mathit{eff}}(\hat{s}))\Big], \qquad (24)\end{aligned}$$

with $\hat{s} = s/m_b^2$, $u(\hat{s}) = \sqrt{[\hat{s} - (1+\hat{m}_s)^2][\hat{s} - (1-\hat{m}_s)^2]}$, $\hat{m}_i = m_i^2/m_b^2$, and the functions $f(\hat{m}_c)$, $\kappa(\hat{m}_c)$, and α_i can be seen in [4]. Here $\Re(C_7^{\mathit{eff}})$ represents the real part of C_7^{eff}. A useful quantity is the differential FB asymmetry in the c.m.s. of the dilepton defined in refs. [33]:

$$\frac{d\mathcal{A}(\hat{s})}{d\hat{s}} = \int_0^1 \frac{d\mathcal{B}}{dz} - \int_0^{-1} \frac{d\mathcal{B}}{dz}, \qquad (25)$$

where $z = \cos\theta$, which can be expressed as:

$$\frac{\mathrm{d}\mathcal{A}(\hat{s})}{\mathrm{d}\hat{s}} = -\mathcal{B}_{sl}\frac{3\alpha^2}{4\pi^2}\frac{1}{f(\hat{m}_c)}u^2(\hat{s})C_{10}\left[\hat{s}\Re(C_9^{\mathit{eff}}(\hat{s})) + 2C_7^{eff}(1+\hat{m}_s^2)\right]. \qquad (26)$$

The Wilson coefficients C_7^{eff}, C_9^{eff} and C_{10} appearing in the above equations can be determined from data by solving the partial branching ratio $\mathcal{B}(\Delta\hat{s})$ and partial FB asymmetry $\mathcal{A}(\Delta\hat{s})$, where $\Delta\hat{s}$ defines an interval in the dilepton invariant mass [32]. From the experimental point of view, the normalized FB-asymmetry, which is defined as

$$\frac{dA(\hat{s})}{d\hat{s}} = \frac{\int_0^1 \frac{d\mathcal{B}}{dz} - \int_0^{-1} \frac{d\mathcal{B}}{dz}}{\int_0^1 \frac{d\mathcal{B}}{dz} + \int_0^{-1} \frac{d\mathcal{B}}{dz}}, \qquad (27)$$

is a more useful quantity. Following branching ratios for the SD-piece have been estimated in [34]:

$$\begin{aligned}\mathcal{B}(B \to X_s e^+ e^-) &= (8.4 \pm 2.2) \times 10^{-6}, \\ \mathcal{B}(B \to X_s \mu^+ \mu^-) &= (5.7 \pm 1.2) \times 10^{-6}, \\ \mathcal{B}(B \to X_s \tau^+ \tau^-) &= (2.6 \pm 0.5) \times 10^{-7}. \qquad (28)\end{aligned}$$

The present best upper limit is $\mathcal{B}(B \to X_s \mu^+ \mu^-) < 3.6 \times 10^{-5}$ at (90% C.L.) by the D0 collaboration [35], and there are no useful limits on the other two decay modes. To get the

physical decay rates and distributions, one has to include the LD-contributions (which are dominated by the J/ψ and ψ' resonances) and the hadronic wave function effects. These aspects have been recently studied in [34], using the Fermi motion model [36] which depends on two parameters p_F (the b-quark kinetic energy) and m_q (the spectator quark mass in $B = \bar{b}q$). We show here the resulting invariant dilepton mass spectrum in Fig. 4, from which it is obvious that only in the dilepton mass region far away from the resonances is there a hope of extracting the Wilson coefficients governing the short-distance physics. The region below the J/ψ resonance is well suited for that purpose for HERA-B as the dilepton invariant mass distribution here is dominated by the SD-piece. The prerequisite for measurements at HERA-B is a lower dilepton

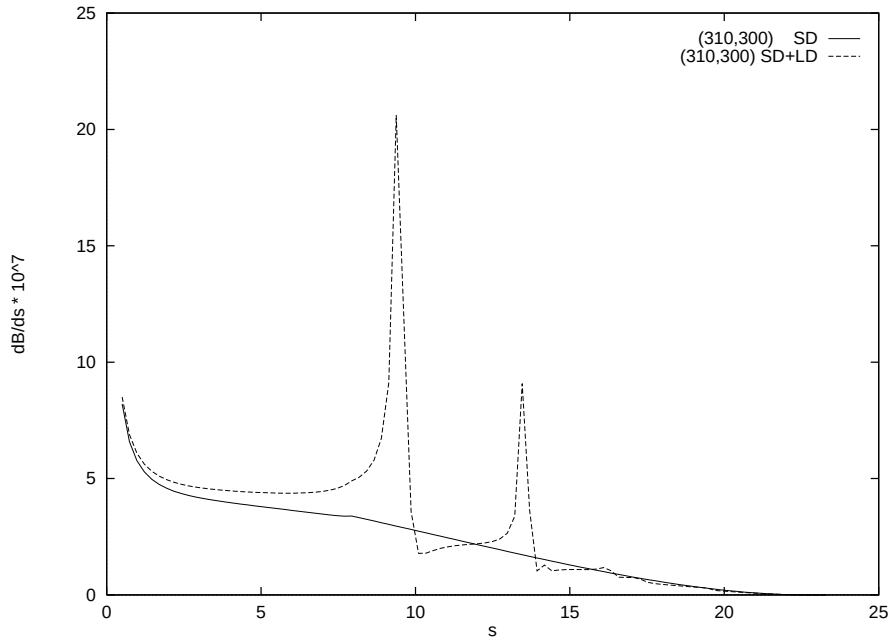

Figure 4: Differential branching ratio $d\mathcal{B}/ds$ for $B \to X_s\ell^+\ell^-$ calculated in the SM using the next-to-leading order QCD corrections and Fermi motion effect (solid curve), and including the LD-contributions (dashed curve). The Fermi motion model parameters (p_F, m_q) are displayed in the figure. (From [34].)

mass trigger than is the case now which is optimized at the J/ψ mass, otherwise the SD-piece in $B \to X_s\mu^+\mu^-$ will be harder to extract. Including the LD-contributions, following branching ratio has been estimated for the dilepton mass range 2.10 GeV^2 $\leq s \leq$ 2.90 GeV^2 in [34]:

$$\mathcal{B}(B \to X_s\mu^+\mu^-) = (1.3 \pm 0.3) \times 10^{-6}, \tag{29}$$

with $\mathcal{B}(B \to X_s e^+e^-) \simeq \mathcal{B}(B \to X_s\mu^+\mu^-)$. The normalized FB-asymmetry is estimated to be in the range 10% - 27%. These branching ratios and the FB asymmetry are expected to be measured within the next several years at HERA-B with few tens of events [23] and other forthcoming B facilities. In the high invariant mass region, the short-distance contribution dominates. However, the rates are down by roughly an order of magnitude compared to the region below the J/ψ-mass. Estimates of the branching ratios are of $O(10^{-7})$, which should be accessible at the LHC.

In conclusion, the semileptonic FCNC decays $B \to X_s\ell^+\ell^-$ (and the related exclusive decays) will provide very precise tests of the SM in flavour physics. They may also reveal new

physics beyond the SM. The MSSM model is a good case study where measurable deviations from the SM are anticipated are anticipated and worked out [32, 37].

3.4 Other topics in B physics

With large samples of B hadrons available, also other precision measurements involving B decays are feasible at HERA-B, e.g. precise determination of $|V_{cb}|$, B-hadron lifetimes and the B^0_d - $\overline{B^0_d}$ mixing ratio x_d. Present measurements of $|V_{cb}|$ are at $\pm 7\%$ [6], and the lifetimes of the specific B hadrons are (all in ps): $\tau(B^{\pm}) = 1.65 \pm 0.04$, $\tau(B^0_d) = 1.55 \pm 0.04$, $\tau(B^0_s) = 1.52 \pm 0.07$ and $\tau(\Lambda_b) = 1.21 \pm 0.06$ [25]. Theoretical estimates based on the QCD-improved parton model predict almost equal lifetimes of the charged ($B^{\pm}$) and neutral (B^0_d, B^0_s) mesons and the Λ_b baryons. Power corrections will split these lifetimes but only moderately. There exists a mild embarrassment for present theoretical estimates in that the ratio $\tau(\Lambda_b)/\tau(B_d) = 0.78 \pm 0.04$ is significantly lower than unity (expected to be > 0.9 in most estimates). To check these models, lifetime have to be measured very accurately, in particular of the Λ_b and B^0_s. Of some theoretical interest is also the lifetime difference between the two mass eigenstates $\Delta\Gamma(B_{s,1} - B_{s,2})$, which is expected to be $O(15\%)$ [39]. Kreuzer showed that lifetime measurements at one to two percent level are feasible for the $B^{\pm}$ and the neutral B^0 mesons, and at $\pm 5\%$ for Λ_b and B^0_s at HERA-B [38]. Another interest lies in the precise determination of Δm_d, [38]. Although the combined LEP and ARGUS/CLEO measurements have reached an accuracy of a few percent with $\Delta M_d = 0.464 \pm 0.018$ $(ps)^{-1}$ [6], HERA-B would be able to contribute to these measurement with comparable errors and very different systematic effects, as it was demonstrated by Kreuzer in this workshop.

The question of producing and detecting the mesons $B_c \equiv \bar{b}c$ (and its charge conjugate) at HERA-B and HERA(ep) was discussed by Baranov, Ivarsson, Mannel, and Rückl at this workshop. This is an interesting object to study, as both the $\bar{b}$ and c quarks can decay independently and $O(5\%)$ decays would take place via the annihilation diagram. The decay products involve final states such as $J/\psi + (\pi, \rho, A_1, ...)$ and the semileptonic decays such as $J\psi\ell^+\nu_\ell$, which are measurable at HERA-B and HERA(ep). Unfortunately, the production cross sections are small at HERA in both the ep and pp modes. Typical estimates are: $\sigma(pp \to B_c\bar{c}bX) \simeq 10\ fb$ at the HERA-B energy $\sqrt{s} \simeq 40$ GeV, with the cross section in the vector meson (B^*_c) mode a factor 2 - 3 larger. This, for example for the $J/\psi\pi$ mode yields $\sigma(B_cX) \cdot \mathcal{B}(J/\psi\pi) = O(10^{-2})fb$, putting its detection beyond the integrated HERA-B luminosity. At HERA(ep), the production cross section is estimated as $\sigma(ep \to B_c\bar{c}bX) \simeq 1\ pb$, making it well nigh impossible to detect the B_c-meson even with an integrated luminosity of 250 $(pb)^{-1}$.

4 Rare Decays, D^0 - $\overline{D^0}$ Mixing and CP Violation

As discussed by Eichler and Frixione in these proceedings, the measured charm hadron photoproduction cross section at HERA is close to one microbarn. At present, a total efficiency of 10^{-4} of charmed hadron reconstruction via D^*-tagging has been achieved at HERA, which is expected to go up to $O(10^{-3})$ by adding various useful decay modes of D^0 and having the benefit of a vertex detector. With an integrated luminosity of 250 $(pb)^{-1}$, and including the

$D^{\pm}$ mesons, this could yield up to 10^6 reconstructed $D^0(\overline{D^0})$ and$D^{\pm}$ events with a $S/N \geq 1$. At HERA-B, the charmed hadron production cross section is estimated as $O(10\ \mu b)$/Nucleon, consistent with the fixed target experiments [40], leading to $O(10^{12})$ charmed hadrons produced in three years of data taking. No detailed study of the charmed hadron reconstruction efficiency has been undertaken at HERA-B. Hence, it is difficult to be quantitative. However, the method of D^*-tagging coupled with vertex resolution studied in the context of HERA will be useful at HERA-B as well. With an (assumed) overall reconstruction efficiency of $O(10^{-5})$ at HERA-B, this would lead to $O(10^7)$ reconstructed charmed events. As reviewed by Jeff Appel during this workshop, fixed target experiments (in particular E791 and E687) have already reconstructed in excess of 10^5 charmed hadrons. A programme to reach $O(10^6)$ charmed hadrons in fixed target experiments in USA is already in place. There are enticing proposals to get to $O(10^8)$ (or even 10^9) charmed hadrons, though the time scale for beyond 10^6 is difficult to predict. It is clear that both HERA and HERA-B have formidable tasks ahead in matching the current and planned performances in the charmed hadron sector.

The current interest in the charm sector lies in doing what has become to be known as "the high impact physics". This means searches for rare decays, D^0 - $\overline{D^0}$ mixing and CP violation. Some of the rare D decays were studied during the previous HERA workshop [41]. An updated study of $D^0 \to \mu^+\mu^-$ has been undertaken by Grab during this workshop [9], with the conclusions that with an integrated luminosity of 250 $(pb)^{-1}$ at HERA, a sensitivity of 2.5×10^{-6} will be reached in this channel. The present upper limit on this decay mode is 7.6×10^{-6} [2]. This implies a factor of 3 improved sensitivity at HERA. The sensitivity in the other leptonic modes $D^0 \to e^+e^-$, $D^0 \to \mu^{\pm}e^{\mp}$ and the semileptonic decays $D^0 \to \rho^0 e^+e^-$, $\rho^0\mu^+\mu^-$, as well as the analogous charged decays $D^{\pm} \to \pi^{\pm}e^+e^-$, $D^{\pm} \to \pi^{\pm}\mu^+\mu^-$ was studied during the previous HERA workshop and can be seen there. In the meanwhile, upper limits on several of these decay modes have moved up significantly [2], leaving a reduced window for searches at HERA.

Finally, we note that both mixing and CP violation in the charm sector are too small to be measured, if the SM is the only source of such transitions. Typically in the SM, one has the following scenario [42]:

$$\frac{\Delta M_D}{\Gamma_D} \simeq O(10^{-5}), \quad \frac{\Delta\Gamma_D}{\Delta M_D} \ll 1, \tag{30}$$

with the CP-violating quantity $Im(\Delta M_d/\Gamma_D)$ negligible. The feature $\Delta\Gamma_D/\Delta M_D \ll 1$ will hold in all extensions of the SM, as the decay rates are determined essentially by the tree diagrams and one does not anticipate large enhancements here. However, in a number of extensions of the SM, the quantity $\Delta M_D/\Gamma_D$ may receive additional contributions pushing it close to its present upper limit [43]. In addition, in some theoretical scenarios, one has $Im(\Delta M_d/\Gamma_D) \simeq Re(\Delta M_d/\Gamma_D)$, implying also measurable CP-violation. This could manifest itself in the differences in the time-dependent and time-integrated rates, leading to CP violating asymmetries in $D^0(t) \to f$ and $\overline{D^0}(t) \to \bar{f}$, where f and $\bar{f}$ are CP-conjugate states. Examples of such extensions are: SUSY models with quark-squark alignment, in which case there are additional contributions to ΔM_D from box diagrams with gluinos and squarks [44], models with a fourth quark generation in which ΔM_D gets new contributions from the W and b' intermediate states [45], models with an $SU(2)$-singlet left-handed up-type quark u'_L, inducing tree-level FCNC couplings, for example in the form of a $Zu\bar{c}$ coupling [46] with implications for the unitarity of the quark mixing matrix, multiscalar models with natural flavour conservation

[47], in which ΔM_D gets new contributions from box diagrams with intermediate charged Higgs $H^{\pm}$ and quarks. Finally, leptoquark models with light scalar leptoquarks [48] may also lead to a large value for ΔM_D; with leptoquark couplings $F_{\ell c} F_{\ell u} \geq 10^{-3}$ and leptoquark masses $M_{LQ} \leq 2$ TeV, new contributions could be of the order of the present experimental bounds [49].

The present limit on D^0 - $\overline{D^0}$ mixing can be expressed in terms of the quantity $r_D \equiv (\Delta M_D/\Gamma_D)^2/[2 + (\Delta M_D/\Gamma_D)^2]$. The decay modes of interest here are $D^0 \to K^+\pi^-$ and $D^0 \to K^+\pi^-\pi^+\pi^-$, which can be reached both via a doubly suppressed Cabibbo (DSC) decay and D^0 - $\overline{D^0}$ mixing. Decay time information is therefore required to distinguish the two mechanisms. The present experimental limit is somewhat porous, namely at 90% C.L. one has $r_D \leq 5.0 \times 10^{-3}$ in each of the two decay modes from the E691 experiment [2], assuming no interference between the DSC- and mixing-amplitudes. As pointed out in [49], taking into account this interference the upper limit is degraded, and one gets instead $r_D < 0.019$ from the $K^+\pi^-$ mode and $r_D \leq 0.007$ from the $K^+\pi^-\pi^+\pi^-$ mode [2]. A monte carlo study to estimate the mixing reach at HERA(ep) has been done by Tsipolitis [10], with the conclusions that a factor of 5 improvement in r_D is conceivable, given the assumed luminosity and vertex resolution.

In the workshop, also experimental developments were discussed. Jeff Appel (FNAL) gave an overview of the physics program at Fermilab in the next years with respect to heavy quark physics. Manfred Paulini (LBL) reported on the achievements of CDF and Kerstin Höpfner (CERN) presented a novel, radiation-hard vertex detector using scintillation fibres.

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