Proceedings of the 20th Lake Louise Winter Institute

Fundamental Interactions

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Fundamental Interactions

PREFACE

The twentieth Lake Louise Winter Institute, entitled Fundamental Interactions, was held from February 20–26, 2005 at the Chateau Lake Louise situated in the scenic Canadian Rocky Mountains. The format of the Winter Institute consisted of a mixture of pedagogical talks and short contributed presentations highlighting the latest results from experiments and new developments in theory. As usual, the sessions were held in the morning till noon and in the evening till at least 10:00 p.m. The participants had ample time for informal discussions in the afternoons or over meals. The afternoons were enjoyed by many for recreation and enjoyment of the winter wonderland in the Rockies.

The pedagogical talks focused on recent developments in cosmology. Results on K- and B-decays were critically assessed to bring out the new understanding of the topic. Results that lead to an unveiling of the new phases of QCD were presented. Physics with atomic traps and its impact on fundamental physics was clearly brought out. Finally the future experiments at the LHC and their discovery potential, in particular discovery of Higgs and possibly finding supersymmetric particles, was clearly spelled out. With the complement of contributed talks, a clear view of the present status of particle physics and cosmology was available.

We wish to thank Lee Grimard for a wonderful organisation of the Winter Institute with care, patience and skill. Our sincere thanks go to Suzette Chan for a masterful job of converting the contributions from the various participants into a nice proceedings. The support and help of the staff at the Chateau was available at all times, making it a rather smooth operation.

Finally we wish to thank the Deans of Science at the University of Alberta and Carleton University, the Institute of Particle Physics and TRIUMF for generous financial support. The Physics Department and Theoretical Physics Institute at the University of Alberta deserve a great deal of thanks for providing the infrastructural support that makes the task of arranging the Winter Institute much easier.

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CONTENTS

NEW PHYSICS IN B AND K DECAYS

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Flavour physics offers interesting probes for the exploration of the Standard Model and the search for new physics. In these lectures, we focus on B- and K-meson decays, introduce the concept of low-energy effective Hamiltonians to describe them theoretically, and discuss how physics beyond the Standard Model may generically affect the roadmap of quark-flavour physics. We address then both the implications of the B-factory data for the $B_d \to J/\psi K_S$ channel and the prospects of $B_s \to J/\psi\phi$ modes for hadron colliders, and discuss how the Standard Model may be challenged through $B_d \to \phi K_S$. Finally, as an example of a systematic flavour strategy to search for new physics, we analyze puzzling patterns in the $B \to \pi\pi, \pi K$ data and study their interplay with rare K and B decays.

1. Introduction

In flavour physics, the parity and charge-conjugation operators $\hat{P}$ and $\hat{C}$, which describe the space-inversion operation and the replacement of all particles by their antiparticles, respectively, play a key rôle. After the discovery that weak interactions are not invariant under parity and charge-conjugation transformations in 1957, it was believed that the product of $\hat{C}$ and $\hat{P}$ was actually preserved. It came then as a big surprise in 1964,[1] when it was observed through the detection of $K_L \to \pi^+\pi^-$ decays that this is actually *not* the case! The corresponding phenomenon is referred to as *CP violation*, and is a central aspect of flavour physics. The manifestation of CP violation discovered in 1964 is "indirect" CP violation, which is described by a complex quantitiy ε_K and originates from the fact that the mass eigenstates of the neutral kaons are not eigenstates of the CP operator. After tremendous experimental efforts, also "direct" CP violation, which is caused *directly* at the amplitude level through the interference between different weak amplitudes, could be established in the neutral kaon system in 1999 by the NA48 (CERN) and KTeV (FNAL) collaborations,[2] thereby ruling out superweak scenarios of CP violation.[3] The world average taking also the final NA48 and KTeV results[4] into account is given as follows:

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (16.6 \pm 1.6) \times 10^{-4}. \tag{1}$$

As far as the theoretical status of this observable is concerned, the short-distance contributions are under full control. On the other hand, the long-distance part, which is described by hadronic matrix elements of certain four-quark operators, suffers from large uncertainties. Although theoretical analyses performed within the Standard Model give results in the ball park of (1), stringent tests cannot be performed unless progress on the long-distance contributions can be made.[5]

In 2001, CP-violating effects were also discovered in the B-meson system by the BaBar (SLAC) and Belle (KEK) collaborations,[6] representing the first observation of this phenomenon *outside* the K-meson system. The corresponding CP asymmetry arises in the "golden" decay $B_d \to J/\psi K_{\mathrm{S}}$,[7] and is induced through the interference between the $B_d^0 \to J/\psi K_{\mathrm{S}}$ and $\bar{B}_d^0 \to J/\psi K_{\mathrm{S}}$ decay processes that is caused by B_d^0–$\bar{B}_d^0$ mixing. In the summer of 2004, also direct CP violation could be detected by the BaBar and Belle collaborations in $B_d \to \pi^{\mp} K^{\pm}$ decays,[8] thereby complementing the observation of this phenomenon in the neutral kaon system.

Despite tremendous progress over the last years, we have still an incomplete picture of CP violation and flavour physics. The exploration of these topics is very exciting, as it may open a window to the physics lying beyond the Standard Model (SM), where quark-flavour physics is governed by the Cabibbo–Kobayashi–Maskawa (CKM) matrix.[9,10] Indeed, in scenarios for new physics (NP), we typically encounter also new sources for flavour-changing processes and CP violation. Important examples are models with extended Higgs sectors, supersymmetric (SUSY) or left–right-symmetric scenarios for NP. In this context, it is also important to note that the experimental evidence for non-vanishing neutrino masses points to an origin beyond the SM, raising many interesting questions, which include also the possibility of CP violation in the neutrino sector.[11]

Interestingly, CP violation plays also an outstanding rôle in cosmology, where this phenomenon is one of the necessary ingredients for the generation of the matter–antimatter asymmetry of the Universe,[12] as was pointed out by Sakharov in 1967.[13] However, model calculations show that the CP violation present in the SM is too small to explain this asymmetry. The required additional sources of CP violation may be associated with very high energy scales, as in the scenario of "leptogenesis", involving CP-violating decays of very heavy Majorana neutrinos.[14] On the other hand, there are also several extensions of the SM with new sources of CP violation that could actually be accessible in the laboratory, as we have noted above.

Before searching for NP, we have first to understand the picture of flavour physics emerging within the SM. Here the usual key problem for the theoretical interpretation is related to hadronic uncertainties, where ε'/ε is a famous example. In the B-meson system, the situation is much more promising: it offers various strategies to explore CP violation and flavour physics – simply speaking, there are *many* B decays – and we may search for SM relations, which are on solid theoretical ground and may well be affected by NP. Concerning the kaon system, the future lies on "rare" decays, which are absent at the tree level of the SM, i.e. originate from loop processes, and are theoretically very clean. A particularly important rôle is played by $K^+ \to \pi^+\nu\bar{\nu}$ and $K_{\rm L} \to \pi^0\nu\bar{\nu}$, which offer poweful tests of the flavour sector of the SM.

These aspects are the focus of these lectures. The outline is as follows: in Section 2, we discuss the description of CP violation in the SM and introduce the unitarity triangle(s). We then move on to the system of the B mesons in Section 3, where we classify non-leptonic B decays, introduce the concept of low-energy effective Hamiltonians, and have a closer look at the CP-violating asymmetries arising in neutral B decays. In Section 4, we turn to rare decays, and discuss $B_{s,d} \to \mu^+\mu^-$ modes as a more detailed example. After addressing the question of how NP may generically enter CP-violating phenomena and rare decays in Section 5, we are well prepared to discuss the "golden" decays $B_d \to J/\psi K_{\rm S}$ and $B_s \to J/\psi\phi$ in Section 6, and how we may challenge the SM through $B_d \to \phi K_{\rm S}$ modes in Section 7. In Section 8, we consider an example of a systematic strategy to search for NP, which is an an analysis of puzzling patterns in the $B \to \pi\pi, \pi K$ data and their interplay with rare K and B decays. Finally, we conclude and give a brief outlook in Section 9.

In order to complement the discussion given here, I refer the reader to the reviews, lecture notes and textbooks collected in Refs. 15–21, where many more details and different perspectives of the field can be found. There are also other fascinating aspects of flavour physics and CP violation, which are, however, beyond the scope of these lectures. Important examples are the D-meson system,[22] electric dipole moments,[23] or the search for flavour-violating charged lepton decays.[24] In order to get an overview of these topics, the reader should consult the corresponding references.

2. CP Violation in the Standard Model

2.1. *Weak Interactions of Quarks*

In the SM of electroweak interactions, CP-violating effects are associated with the charged-current interactions of the quarks:

$$D \to UW^-. \tag{2}$$

Here $D \in \{d, s, b\}$ and $U \in \{u, c, t\}$ denote down- and up-type quark flavours, respectively, whereas the W^- is the usual $SU(2)_\mathrm{L}$ gauge boson. From a phenomenological point of view, it is convenient to collect the generic "coupling strengths" V_{UD} of the charged-current processes in (2) in the form of a 3×3 matrix. From a theoretical point of view, this "quark-mixing" matrix – the CKM matrix – connects the electroweak states (d', s', b') of the down, strange and bottom quarks with their mass eigenstates (d, s, b) through the following unitary transformation :

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix} \equiv \hat{V}_\mathrm{CKM} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}. \tag{3}$$

Consequently, $\hat{V}_\mathrm{CKM}$ is actually a *unitary* matrix. This feature ensures the absence of flavour-changing neutral-current (FCNC) processes at the tree level in the SM, and is hence at the basis of the Glashow–Iliopoulos–Maiani (GIM) mechanism.[25] If we express the non-leptonic charged-current interaction Lagrangian in terms of the mass eigenstates in (3), we arrive at

$$L_\mathrm{int}^\mathrm{CC} = -\frac{g_2}{\sqrt{2}} \left(\bar{u}_\mathrm{L}, \bar{c}_\mathrm{L}, \bar{t}_\mathrm{L} \right) \gamma^\mu \hat{V}_\mathrm{CKM} \begin{pmatrix} d_\mathrm{L} \\ s_\mathrm{L} \\ b_\mathrm{L} \end{pmatrix} W_\mu^\dagger + \mathrm{h.c.}, \tag{4}$$

where g_2 is the $SU(2)_\mathrm{L}$ gauge coupling, and the $W_\mu^{(\dagger)}$ field corresponds to the charged W bosons. Looking at the interaction vertices following from (4), we observe that the elements of the CKM matrix describe in fact the generic strengths of the associated charged-current processes, as we have noted above.

Since the CKM matrix elements governing a $D \to UW^-$ transition and its CP conjugate $\bar{D} \to \bar{U}W^+$ are related to each other through

$$V_{UD} \xrightarrow{CP} V_{UD}^*, \tag{5}$$

we observe that CP violation is associated with complex phases of the CKM matrix. Consequently, the question of whether we may actually have *physical* complex phases in this matrix arises.

2.2. *Phase Structure of the CKM Matrix*

We may redefine the up- and down-type quark fields as follows:

$$U \to \exp(i\xi_U)U, \quad D \to \exp(i\xi_D)D. \tag{6}$$

If we perform such transformations in (4), the invariance of the charged-current interaction Lagrangian implies

$$V_{UD} \to \exp(i\xi_U)V_{UD}\exp(-i\xi_D). \tag{7}$$

Eliminating unphysical phases through these transformations, we are left with the following parameters in the case of a general $N \times N$ quark-mixing matrix, where N denotes the number of fermion generations:

$$\underbrace{\frac{1}{2}N(N-1)}_{\text{Euler angles}} + \underbrace{\frac{1}{2}(N-1)(N-2)}_{\text{complex phases}} = (N-1)^2. \tag{8}$$

If we apply this expression to $N = 2$ generations, we observe that only one rotation angle – the Cabibbo angle θ_C[9] – is required for the parametrization of the 2×2 quark-mixing matrix, which can be written as

$$\hat{V}_C = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix}, \tag{9}$$

where $\sin\theta_C = 0.22$ follows from $K \to \pi\ell\bar{\nu}_\ell$ decays. On the other hand, in the case of $N = 3$ generations, the parametrization of the corresponding 3×3 quark-mixing matrix involves three Euler-type angles and a single *complex* phase. This complex phase allows us to accommodate CP violation in the SM, as was pointed out by Kobayashi and Maskawa in 1973.[10] The corresponding picture is referred to as the Kobayashi–Maskawa (KM) mechanism of CP violation.

In the "standard parametrization" advocated by the Particle Data Group,[26] the three-generation CKM matrix takes the following form:

$$\hat{V}_{\mathrm{CKM}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}, \tag{10}$$

where $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} \equiv \sin\theta_{ij}$. If we redefine the quark-field phases appropriately, θ_{12}, θ_{23} and θ_{13} can all be made to lie in the first quadrant. The advantage of this parametrization is that the mixing between two generations i and j vanishes if θ_{ij} is set to zero. In particular, for $\theta_{23} = \theta_{13} = 0$, the third generation decouples, and the submatrix describing the mixing between the first and second generations takes the same form as (9).

2.3. *Wolfenstein Parametrization*

The charged-current interactions of the quarks exhibit an interesting hierarchy, which follows from experimental data:[26] transitions within the same generation involve CKM matrix elements of $O(1)$, those between the first and the second generation are associated with CKM elements of $O(10^{-1})$, those between the second and the third generation are related to CKM elements of $O(10^{-2})$, and those between the first and third generation are described by CKM matrix elements of $O(10^{-3})$. For phenomenological applications, it would be useful to have a parametrization of the CKM matrix available that makes this pattern explicit.[27] To this end, we introduce a set of new parameters, λ, A, ρ and η, by imposing the following relations:[28]

$$s_{12} \equiv \lambda = 0.22, \quad s_{23} \equiv A\lambda^2, \quad s_{13}e^{-i\delta_{13}} \equiv A\lambda^3(\rho - i\eta). \tag{11}$$

Going back to the standard parametrization (10), we obtain an *exact* parametrization of the CKM matrix as a function of λ (and A, ρ, η), which allows us to expand each CKM element in powers of the small parameter λ. Neglecting terms of $O(\lambda^4)$ yields the "Wolfenstein parametrization":[27]

$$\hat{V}_{\text{CKM}} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4). \tag{12}$$

2.4. *Unitarity Triangle(s)*

The unitarity of the CKM matrix, which is described by

$$\hat{V}^\dagger_{\text{CKM}} \cdot \hat{V}_{\text{CKM}} = \hat{1} = \hat{V}_{\text{CKM}} \cdot \hat{V}^\dagger_{\text{CKM}}, \tag{13}$$

leads to a set of 12 equations, consisting of 6 normalization and 6 orthogonality relations. The latter can be represented as 6 triangles in the complex plane, all having the same area, which represents a measure of the "strenghth" of CP violation in the SM.

Using the Wolfenstein parametrization of the CKM matrix, the generic shape of these triangles can be explored. Interestingly, only the following two orthogonality relations correspond to the case of triangles, where all three sides are of the same order of magnitude:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \tag{14}$$

$$V_{ud}^*V_{td} + V_{us}^*V_{ts} + V_{ub}^*V_{tb} = 0; \tag{15}$$

in the other triangles, one side is suppressed with respect to the others by factors of $O(\lambda^2)$ or $O(\lambda^4)$. If we apply the Wolfenstein parametrization by

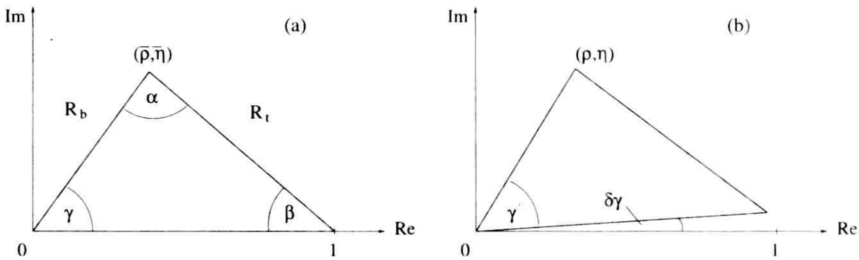

Figure 1. The two non-squashed unitarity triangles of the CKM matrix, as explained in the text: (a) and (b) correspond to the orthogonality relations (14) and (15), respectively.

keeping just the leading, non-vanishing terms of the expansion in λ, (14) and (15) give the same result, which is given by

$$[(\rho + i\eta) + (1 - \rho - i\eta) + (-1)]\, A\lambda^3 = 0, \tag{16}$$

and describes *the* unitarity triangle of the CKM matrix. Taking also the next-to-leading order corrections in λ into account,[28] as described in Subsection 2.3, we arrive at the triangles illustrated in Fig. 1. The apex of the triangle in Fig. 1 (a) is simply given by

$$\bar\rho \equiv \rho\left[1 - \frac{1}{2}\lambda^2\right], \quad \bar\eta \equiv \eta\left[1 - \frac{1}{2}\lambda^2\right], \tag{17}$$

corresponding to the triangle sides

$$R_b \equiv \left[1 - \frac{\lambda^2}{2}\right]\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|, \quad R_t \equiv \frac{1}{\lambda}\left|\frac{V_{td}}{V_{cb}}\right|. \tag{18}$$

Obviously, this triangle is the straightforward generalization of the leading-order case, and is usually considered in the literature. Whenever referring to *a* unitarity triangle (UT) in the following discussion, we shall always mean this triangle. On the other hand, the characteristic feature of the triangle in Fig. 1 (b) is that $\gamma = \gamma' + \delta\gamma$, with

$$\delta\gamma = \lambda^2\eta = O(1^\circ). \tag{19}$$

2.5. *Determination of the Unitarity Triangle*

There are two conceptually different avenues to determine the UT:

(i) In the "CKM fits", theory is used to convert experimental data into contours in the $\bar\rho$–$\bar\eta$ plane, where semileptonic $b \to u\ell\bar\nu_\ell$, $c\ell\bar\nu_\ell$ decays and $B^0_{d,s}$–$\bar B^0_{d,s}$ mixing (see 3.1) allow us to determine the

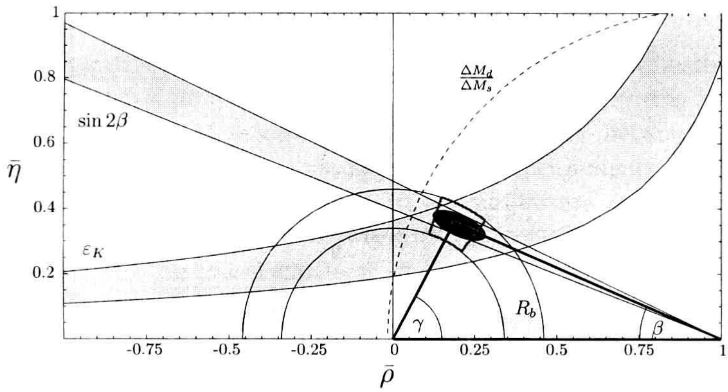

Figure 2. The current situation in the $\bar{\rho}$–$\bar{\eta}$ plane, as discussed in the text.

UT sides R_b and R_t, respectively, i.e. to fix two circles in the $\bar{\rho}$–$\bar{\eta}$ plane. On the other hand, the indirect CP violation in the neutral kaon system described by ε_K can be transformed into a hyperbola.

(ii) Theory allows us to convert measurements of CP-violating effects in B-meson decays into direct information on the UT angles. The most prominent example is the determination of $\sin 2\beta$ through $B_d \to J/\psi K_S$, but several other strategies were proposed.

The goal is to "overconstrain" the UT as much as possible. In the future, additional contours can be fixed in the $\bar{\rho}$–$\bar{\eta}$ plane through the measurement of rare decays. For example, $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$ can be converted into an ellipse, and $\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})$ allows the determination of $|\bar{\eta}|$.

In Fig. 2, we show the current situation: the shaded dark ellipse is the result of a CKM fit,[29] the straight lines represent the measurement of $\sin 2\beta$ (see Subsection 6.1), and the quadrangle corresponds to a determination of γ from $B_d \to \pi^+\pi^-$, $B_d \to \pi^\mp K^\pm$ decays,[30] which will be discussed in Section 8. For very comprehensive analyses of the UT, we refer the reader to the web sites of the "CKM Fitter Group" and the "UTfit collaboration".[31]

The overall consistency with the SM is very impressive. Furthermore, also the recent data for $B \to \pi\rho, \rho\rho$ as well as $B_d \to D^{(*)\pm}\pi^\mp$ and $B \to DK$ decays give constraints for the UT that are in accordance with the KM mechanism, although the errors are still pretty large in several of these cases. Despite this remarkably consistent picture, there is still hope to encounter deviations from the SM. Since B mesons play a key rôle in this adventure, let us next have a closer look at them.