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Flavour physics and CP violation / Physique de la saveur et violation de CP

Foreword

This “dossier” deals with “CP violation” and “Flavour physics”, two deeply entangled frontier domains, not only of particle physics, but also of our understanding of physics in general – in particular, the existence of a preferred orientation of time, already at the microscopic level, independently of entropic considerations.

The initial goal was to discuss just “CP violation”, but we decided quickly that it was impossible to separate the two topics. Clearly, we should first explain what CP violation is, and why it is an important issue. Quite simply, C refers to “charge conjugation”, that is reversing the “charges” (including the electric charge) of all particles, and P to spatial reflection, as seen in a mirror. Violation of CP symmetry means, in particular, that we can define both particles and antiparticles in an absolute way: there is a subtle distinction between matter and antimatter, so that we can identify one without having a sample of the other for comparison. In the same way, we can define a “right” hand in absolute terms (without referring to the left hand). On a theoretical level, CP violation is deeply related to time reversal (T), and experiment proves that the observed CP violation is associated with a lack of reversibility at the microscopic level.

CP violation is essential to exploring “New Physics”, beyond the “Standard Model” (SM). First of all, CP symmetry is the exact symmetry of gauge interactions, the part of the SM (analogous to electromagnetism) which we understand best. As a result, it can only be described by the as yet ill-understood “scalar” sector (or by New Physics), which it probes directly. Within the Standard Model, all *currently observed* CP violation is deeply linked to the presence of at least 3 families of particles (six flavours of quarks, 3 of charged leptons), hence the fundamental interconnection of the two subjects.

Another important issue is the extreme sensitivity of the tests performed in CP and flavour physics. This extreme sensitivity makes it possible to look for New Physics that is yet inaccessible even to the highest energy facilities, in particular, the Large Hadron Collider (LHC) at CERN.

This should not be a big surprise. In fact, the whole history of weak interactions stems from the effect of “virtual” particles. Indeed, the very name “weak interactions” used to describe the beta decay of nuclei indicates that we were facing a small effect. It was quickly suspected that the weak interactions could be “mediated” by heavy vector bosons, but the experimental discovery of the W and Z bosons, nearly two orders of magnitude above the proton mass and 5 orders of magnitude above the energy exchanged in weak decays, took decades and generations of accelerators.

The same is true now when we look at flavour and CP issues. The smaller the effect probed, or the more accurate the measurement, the higher the mass range of virtual particles probed. For this reason we need to observe enormous numbers of decays, and hence to use very intense beams of particles – what we call “high luminosity”. These searches – often named “indirect” or “high-precision” measurements, enable us to probe NP energy scales inaccessible to present and next-generation colliders. One should remember, however, that while observing a low-energy indirect effect proves the presence of something new and may provide powerful hints to its nature, high-energy facilities remain necessary to bring the final elucidation (just like what happened for the W and Z bosons, elucidating the Fermi model).

To return to the specific subject of this issue, we have already stated that the best-known (and established) part of the Standard Model, namely the Gauge interactions (the direct generalisation of the photon), respects the CP and T symmetries (*these are in fact the natural symmetries of Gauge interactions*), but we must also remember that they prevent, to a high degree, *flavour changing neutral* interactions (which means that neither the photon nor the Z boson Lagrangian couplings allow for changes in quark or lepton flavour).

For this reason, all departures from the above (namely Flavour Changing Neutral Currents – FCNC – or CP/T violations) must be blamed either on the worst-known part of the Standard Model (it’s as yet unresolved Scalar sector) or on New Physics.

Historically, various mechanisms were proposed to describe CP violation and/or the suppression of neutral flavour changing interactions. In time, the Cabibbo–Kobayashi–Maskawa mixing (CKM) mechanism, a very minimal model, emerged.

In this approach, the suppression of the mixing among neutral K mesons, and of their leptonic decays, were the clue to predicting both the existence and the approximate mass of the “charm” quark (completing the 2nd family and establishing the fermion family pattern). Further, the existence of a 3rd family of fermions (the top and bottom quarks) was predicted from the presence of CP violation.

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This very minimalist model, built on the knowledge of CP violation only in the Kaon system, was later confirmed in a rather spectacular way by measurements at B factories.

This was a very important contribution: indeed, all alternative models (including Supersymmetry, Left–Right models, …) predicted, or at least allowed for some deviations, and are in fact currently *constrained* by the B physics data.

To some extent, this result is also surprising because another source of CP violation beyond the CKM mechanism must exist, notably to account (through baryo- or leptogenesis) for the current dominance of matter over antimatter in our Universe. It is also somewhat frustrating because the parameters entering the scalar sector are quite arbitrary, and currently escape our deeper understanding: a nagging situation for a fact as fundamental as the existence of a preferred orientation of time… Clearly, some deeper origin of mass patterns, of the replication of families, and of the scalar sector in general, must be sought.

Today, the CKM scheme is well established and describes successfully the bulk of the data. Of course, the search continues, with more precise measurements, new channels. Discrepancies can arise, are actively looked for, and can be interpreted as hints of New Physics. The quantitative comparison between precision measurements and the SM is oftentimes made difficult by the presence of strong interactions, and progress in the theoretical evaluation of weak matrix elements is needed as much as increased experimental accuracy. At the same time, completely new channels open up (with the "Strange B mesons" Bs sector accessible through Tevatron, LHC general-purpose experiments, and also the dedicated LHCb collaboration). This allows for new probes.

Let us turn now to the organisation of this thematic issue, where we have tried to provide a basic introduction, some in-depth analysis of the main concepts, and also some insight into the evolution of the field and a perspective on future developments. The presentation also moves from the "traditional" quark-flavour sector into new territory (at least in terms of experimental evidence): strong CP violation and electric dipole moments, CP violation in charged leptons or in neutrinos, mechanisms for generating the matter–antimatter asymmetry of the Universe.

The first articles are meant to present the concepts. The presentation starts with the meaning and importance of CP and T violation (*J.-M. Frère*).

The fact that CP violation can be discussed in a basis-independent way is very important for our understanding of the phenomenon, of the size of its effects (and maybe in order to hunt for its origin), and is presented here by its initiator (*C. Jarlskog*).

M. Ciuchini and L. Silvestrini first introduce the basic formalism and notations in the Standard Model (CKM context), and then extend the discussion of flavour and CP violation beyond the Standard Model, and show how flavour physics is a privileged tool for seeking New Physics.

As already mentioned, a very important ingredient in these studies is control of the strong interactions and mainly in a non-perturbative regime: *D. Beciveric and V. Lubicz* present the progress made using the currently most promising tool, namely massive numerical calculations, to solve Quantum Chromodynamics (QCD) on lattices.

With this basis in place, we shift to more topical issues in the quark domain, before moving on to the non-CKM and leptonic sectors.

Kaon physics is where it all started, but it combines a glorious past and a bright future, yielding an incredible laboratory for seeking rare processes. This is reviewed by *J.-M. Gerard and P. Valente*.

Charm physics has always been a difficult field, for both experiment and theoretical evaluations (the quark is neither "light" nor "heavy", defying thereby the usual approaches, and decay competes strongly with oscillations. Challenging experimental data, including data on charm mixing, indicate, however, that *charm physics* could play an important role in the search for New Physics, in particular through CP violation. Prospects are discussed by *I. Bigi and P. Roudeau*.

We now turn to the B factories. They have proven to be the second "workhorse" of CP and flavour violation, first because they offered an independent test of the CKM predictions. Before them, all CP violation was confined to the Kaon system and the measurement of only two parameters. This revolution is evoked here by one of its key promoters, *A.I. Sanda*, and the B factory legacy is presented by *A. Bevan*.

The detailed study of all these quark sector measurements of flavour and CP violating interactions is of course motivated by the hunt for departures from the minimal assumption (now the CKM model). Even though the bulk of data support it, small discrepancies may show us the way to New Physics. We have included as an example of such a search the contribution of *E. Lunghi and A. Soni*, who point out the tensions in the current approach, and discuss how, despite the QCD-related uncertainties, they could be a hint of physics beyond the SM.

Most of the results in B physics in the next few years are expected to come from the ongoing LHCb experiment at CERN. This is precisely the subject of the next contribution, by *A. Stocchi and M.-H. Schune*. In this contribution the most interesting measurements in the physics programme of the next-generation flavour factory are also reviewed and compared with what can be expected from on-going work at existing facilities.

After quark flavour physics, where CP issues are strongly established, we turn to new "discovery" sectors.

The first is the study of Electric Dipole Moments (EDMs). While an electric dipole moment is certainly not an exotic feature of composite states (such as a water molecule), EDMs are a clear violation of CP (or T) for elementary particles (leptons, quarks – the latter reflecting on nucleons), as they would need to align on the spin direction, a clear violation of P. It is a curious circumstance that EDMs are strongly suppressed in the Standard Model (with the possible exception of strong CP violation). Therefore, EDM measurements must be regarded as an exceptionally clean place to look for New Physics, and in fact, most theories beyond the Standard Model (BSM) predict rather large EDMs … *their parameter space is in fact restricted* *already by the current measurements*. EDMs are discussed here by *O. Navillat and R. Timmermans,* while the Strong CP problem is discussed by *P. Sikivie*.

Moving now resolutely away from the quark sector, we turn to prospects for exploring the similar structure for leptons. Here experimental evidence of CP violation is currently lacking, while flavour changing effects have only been seen through neutrino oscillations. Some richer aspects of CP violations could be linked to the nature of neutrinos, as more phases (but only observable in neutrinoless double beta decay) are available for Majorana neutrinos.

Not unlike EDMs, charged lepton flavour violation is strongly suppressed in the Standard Model, which makes this search one of the most powerful probes of New Physics. This issue is discussed here by *A. Abada.*

An introduction to CP violation in neutrinos and to prospects for its detection are presented in depth by *P. Hernandez*.

The particular importance of CP violation in the lepton sector stems from its possible role in the "defeat of antimatter". Namely, if the Universe was created through gravitational interactions, we would expect exact symmetry between matter and antimatter, in clear opposition to the current situation. Leptogenesis offers a very robust (but therefore hard to test) mechanism for generating this asymmetry. The subject is reviewed by *T. Hambye* in the last article of this dossier.

Jean-Marie Frère
Service de physique théorique, université libre de Bruxelles, boulevard du Triomphe, B-1050 Bruxelles, Belgium
E-mail address: frere@ulb.ac.be

Achille Stocchi
Laboratoire de l'accélérateur linéaire, IN2P3-CNRS et université de Paris-Sud, BP 34, 91898 Orsay cedex, France
E-mail address: stocchi@lal.in2p3.fr

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