Particle physics: Charming clue for our existence

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ABSTRACT

The LHCb collaboration announced the observation of CP violation in the decays of the D^0 meson, the lightest particle containing charm quarks, which might provide clues to why there is more matter than antimatter in the Universe and lead to a deeper understanding of the theory of the strong interaction.

The visible part of our Universe is mostly made up of protons and some neutrons and each proton is to a good approximation made out of two up quarks and one down quark. This immediately raises two questions. First, starting from symmetric initial conditions in the very early Universe, we would expect an equal number of particles and anti-particles. Where are all the anti-protons? Second, since up and down quarks seem to be sufficient to describe our world, why are there also heavier copies of the up-quark, such as the charm and the top quark and heavier copies of the down-quark, such as the strange and the bottom quark?

In 1967 Andrei Sakharov[1] found three criteria for any fundamental theory of nature, that enable the creation of a matter-antimatter asymmetry out of a symmetric initial state at the beginning of the Universe. One of these requirements is the violation of a symmetry called CP: the charge (C) transformation makes a negative charged particle out of a positive one and the parity (P) transformation exchanges left with right, that is all coordinates $\vec{x}$ are transformed into $-\vec{x}$. In 1973 Makoto Kobayashi and Toshihide Maskawa[2] showed that in the standard model of particle physics (SM) at least two heavier copies of the up and the down quark are necessary in order to have CP violation for quarks. So in principle the SM contains the necessary ingredient of CP violation, but whether it contains enough of it, that is a different question.

CP violation has so far been confirmed experimentally in composite particles containing strange or bottom quarks and it is currently intensively studied by the LHCb collaboration and the ATLAS and CMS experiments at the Large Hadron Collider (LHC) at CERN and soon by the Belle II experiment in Japan. Unfortunately it turned out that the amount of CP violation found for the strange and bottom quarks is not sufficient to explain the matter-antimatter asymmetry in the Universe. Naive SM estimates predict a tiny amount of CP violation for the charm quarks, therefore it came as a big surprise when the LHCb Collaboration announced at a workshop dinner in Geneva in 2011 the first evidence for a large value of a quantity denoted ΔA_{CP} (see Ref.[3]). This quantity describes the different probabilities for a D^0 meson (consisting of a charm and an anti-down quark, see Fig. 1 a) to decay into a pion $\pi^+ = (u\bar{d})$ - $\pi^- = (d\bar{u})$ pair, where d and u stand for the down and up quarks respectively and the bar denotes the antiparticle, and for a $\bar{D}^0 = (\bar{c}u)$ meson, where c stands for the charm quark, decaying into the same final state. To increase the experimental accuracy, this difference is compared to the equivalent difference if the final state consists of kaons $K^+ = (u\bar{s})$ and $K^- = (s\bar{u})$, where s denotes the strange quark.

The 2011 measurement prompted hundreds of scientific papers, either interpreting it as evidence for new sources of CP violation or as new unknown large effects of the strong interaction within the SM. Unfortunately follow-up measurements could not confirm the first evidence for CP violation for particles containing charm quarks and the interest in the topic somewhat faded so the first chapter of the ΔA_{CP} saga seemed to have come to an end[4]. Nevertheless the LHCb collaboration continued measuring this quantity with much larger datasets, and finally in March this year, they announced[5] the definite observation of a non-vanishing value of ΔA_{CP} at the Moriond Conference. The new value is smaller than the one found in 2011, but it is still a factor of at least five to ten times larger than naive SM expectations.

Less than a week after the LHCb announcement, three theory paper appeared on the arxiv preprint server. Based on more elaborated estimates they came again to opposite conclusions: the new measurement is probably due to physics beyond the SM (Ref.[6]) versus the new effects can be accommodated within the SM (Ref.[7,8]). At the beginning of April all three scientific teams met at a workshop at Durham University to discuss their contradicting ideas.

Where do these conflicting interpretations root? Often the mathematical equations describing the SM cannot be solved exactly and we can describe an observable A only approximately, or more rigorously we can express A as a Taylor series with an expansion parameter x and Taylor coefficients a_i:

$$A = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + \ldots .$$

Typically it turns out that the higher terms in this expansion are considerably more difficult to calculate than the lower terms and state-of-the art mathematical techniques allow only the determination of the first two or three coefficients. If the coefficients a_i are all of similar magnitude and if x is a small number, for instance $x = 0.1$, then we expect a nicely converging series

$$A = a_0 + 0.1\,a_1 + 0.01\,a_2 + 0.001 a_3 + \dots,$$

which can be well approximated by the first few terms. If x is, however, of the order one, all coefficients a_i contribute with a similar weight and in order to determine the observable A one has to know an infinite number of coefficients which is a clear impossibility.

The theoretical understanding of the new LHCb result for the CP violating quantity ΔA_{CP} boils now down to the determination of the size of the expansion parameter x in the composite particle containing charm quarks. The decay of a D^0 meson into a $\pi^+ - \pi^-$ pair can proceed via two possibilities: the left of Fig. 1b shows the space-time diagram (a Feynman diagram with time on the horizontal axis) of the dominant contribution to this decay - the tree-level amplitude; the right of Fig. 1b shows the Feynman diagram of a more complicated decay path - the so-called penguin amplitude. The numerical evaluation of a Feynman diagram gives the probability of the corresponding process. To some extent the expansion parameter x can in this case be imagined as the ratio of the numerical value of the penguin Feynman diagram relative to the tree-level Feynman diagram - if $x \approx 0.1$ then the SM contribution to ΔA_{CP} is small and the new experimental measurement is due to physics beyond the SM; if $x \approx 1$ then the new measurement would be due to very large hadronic effects within the SM.

The authors of Ref.[7] assume that x is large and with the help of additional symmetries that imply that the up, down and strange quark behave similarly (SU(3) flavour symmetry), they find a consistent theoretical picture for the description of hadronic D meson decays and conclude thus that the measured value of LHCb can be well accommodated by the SM.

In Ref.[6] we follow a different approach and start from the observation that we can describe theoretically the measured lifetimes of the D mesons well with our theoretical tools[9] and we find an expansion parameter of $x \approx 0.3$ so a Taylor expansion could make sense.This observation is based on some considerable theoretical effort in determining four of the subleading coefficients in the Taylor expansion. We are therefore confident that the first principle quantum chromodynamics tools (which work only for small x) used in Ref.[10] will give reliable predictions in the charm system and we predict[6] that the LHCb measurement of CP violation[5] is about a factor of 7 larger than the SM prediction and this deviation could be due to new physics. Whether this will be sufficient to explain the missing anti-matter in the Universe will have to be worked out in future studies, as well as precise limits of the possible hadronic contributions in charm physics. So a new chapter of the ΔA_{CP} saga still opened and there is a lot of exciting work ahead of us.

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Competing interests

The authors declare no competing interests. Please edit as necessary. Note that the information must be the same as in our manuscript tracking system.

Publisher's note

Figure 1. Six different types of quarks are known to exist in nature. More or less all matter around us is made of the up (u) and the down quark (u); for example two up quarks and one down quark form a proton. But there are heavier copies of these two quarks: charm (c) and top (t) quarks, which have the same electric charge (+2/3) as the up quarks, and strange (s) and bottom (b) quarks have the same electrical charge (-1/3) as the down quarks. The charm quark together with an anti-up quark can form a bound state called D^0. There are two ways in which D^0 can decay into a pair of pions (consisting of up and down quarks and their antiparticles): the so-called tree level decay (left) and the more complicated penguin decay (right).