NEWS & VIEWS

PARTICLE PHYSICS

Charming clue for our existence

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The Large Hadron Collider beauty experiment (LHCb) collaboration announced the observation of charge parity (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.

Refers to LHCb collaboration. Observation of CP violation in charm decays. Preprint at *arXiv* https://arxiv.org/abs/1903.08726 (2019).

The visible part of our Universe is mostly made up of protons and some neutrons, and each proton is, to a good approximation, made 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 antiparticles; however, where are all the anti-protons? Second, since up quarks 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 quark and the top quark, and heavier copies of the down quark, such as the strange quark and the bottom quark?

In 1967 Andrei Sakharov found three criteria[1] for any fundamental theory of nature that enables 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 showed[2] that in the standard model (SM) of particle physics at least two heavier copies of the up quark and the down quark are necessary in order to have CP violation for quarks. Therefore, in principle the SM contains the necessary ingredient of CP violation, but whether it contains enough of it is a different question.

CP violation has so far been confirmed experimentally in composite particles containing strange quarks or bottom quarks and it is currently intensively studied by the Large Hadron Collider beauty experiment (LHCb) collaboration and the ATLAS and compact muon solenoid (CMS) experiments at the LHC at CERN, and soon by the Belle II experiment in Japan. Unfortunately, the amount of CP violation found for the strange quarks 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 quark; 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} (REF.[3]). This quantity describes the different probabilities for a $D^0 = (c\bar{u})$ meson, consisting of a charm quark and an anti-up quark (see FIG. 1a), to decay into a pion $\pi^+ = (u\bar{d}) - \pi^+ = (u\bar{d})$ pair, where d and u stand for the down quarks 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 with 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, thus 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 at least five to ten times larger than naive SM expectations.

Less than a week after the LHCb announcement, three theory papers 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[6] versus the new effects can be accommodated within

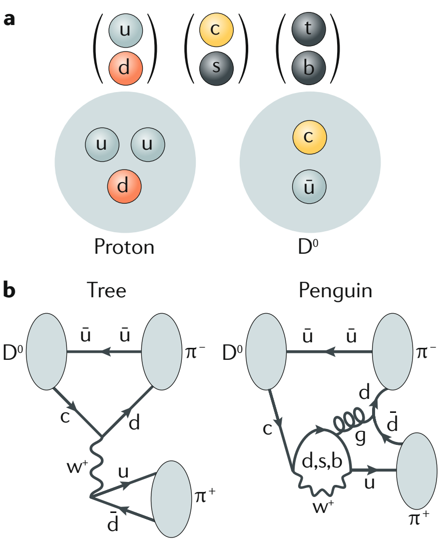

Fig. 1 | **Six different types of quarks are known to exist in nature. a** | More or less all matter around us is made of the up quark (u) and the down quark (u); for example, two up quarks and one down quark form a proton. However, there are heavier copies of these two quarks: charm quarks (c) and top quarks (t), which have the same electrical charge (+2/3) as the up quarks, and strange quarks (s) and bottom quarks (b), which 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. **b** | There are two ways in which D^0 can decay into a pair of pions π (consisting of up quarks and down quarks and their antiparticles): the so-called tree level decay (left-hand side) and the more complicated penguin decay (right-hand side). The wavy line corresponds to the W-boson mediated weak interaction and the curly line to the gluon-mediated strong interaction.

the SM[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:

$$A = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + \cdots \qquad (1)$$

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 example, $x = 0.1$, then we expect a nicely converging series:

$$A = a_0 + 0.1 a_1 + 0.01 a_2 + 0.001 a_3 + \cdots \qquad (2)$$

which can be well approximated by the first few terms. If x is, however, of the order 1, 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 down to the determination of the size of the expansion parameter x in the composite particle containing charm quarks. There are two possible pathways for the decay of a D^0 meson into a π^+–π^- pair. The left-hand side 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-hand side of FIG. 1b shows the Feynman diagram of a more complicated decay path: the so-called penguin amplitude. To some extent the expansion parameter x in this case can 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 is 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 quark, down quark and strange quark behave similarly (SU(3) flavour symmetry), they find a consistent theoretical picture for the description of hadronic D meson decays and thus conclude 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 theoretically describe 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 approximately a factor of seven larger than the SM prediction and this deviation could be due to new physics. Whether this will be sufficient to explain the missing antimatter 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.

A new chapter of the ΔA_{CP} saga has been opened and there is a lot of exciting work ahead of us.

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Competing interests

The authors declare no competing interests.