A Charmed Tetraquark at LHC*

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The quark model of hadrons (i.e., particles whose interactions are mediated by strong interactions) was postulated by Gell-Mann and Zweig in 1964 in which the mesons (like pion, Kaon, etc.) were formed out of $q\bar{q}$ pairs and the baryons (proton, neutron, etc.) out of qqq triplets [1]. The quarks interact via gluons and are subject to confinement inside the nuclear volume according to current theories. Apart from their mass, spin and electric charge, the quarks have additional quantum numbers, flavour and colour, assigned to them as they obey certain symmetries. There are six flavours, viz., up(u), down(d), strange(s), charm(c), bottom or beauty(b) and top or truth(t). Out of these, the first three are light quarks, and the last three are much heavier with the top being the heaviest. Each flavour can have three colours, red, blue, and green so that the hadrons are colour neutral. The colours have nothing to do with the visible colours in optics but are akin to the charge in electromagnetism. This model successfully describes the properties of hadrons and their interactions and is known as quantum chromodynamics (QCD)—the theory of strong interactions. Even the early quark model did not preclude the hadrons to be composed of four or more quarks. States composed of quarks and gluons beyond conventional mesons ($q\bar{q}$) and baryons (qqq) are termed exotic hadrons.

Study of exotic hadrons can provide new insights into the internal structure and the confinement mechanism and also act as a unique probe to non-perturbative behaviour of QCD. The first experimental evidence for an exotic hadron candidate was the X(3872) state observed in 2003 by the Belle collaboration [2]. Since then, a series of novel states consistent with four-quark composition have been discovered. The LHCc collaboration has also observed resonances interpreted to be pentaquark states. But the first unambiguous experimental evidence of the existence of these exotic hadrons came, when the Z(4430)$^-$ particle, first observed by the Belle collaboration, was shown to be composed of four quarks ($c\bar{c}d\bar{u}$) by the LHCc collaboration in 2014 [3].

All hadrons observed so far, including those of exotic nature, contain at most two heavy charm (c) or two bottom (b) quarks, whereas many QCD-motivated phenomenological models also predict the existence of states consisting of four heavy quarks, i.e. $X_{q1q2q3q4}$, where qi is a c or a b quark. Search for such heavy tetraquarks has been going on at LHCb since the Large Hadron Collider (LHC) started operating in 2009. The motivation for this search is that hadrons containing the heavy flavours (charm and bottom) are easier to understand in terms of QCD compared to light quark hadrons. Due to their large masses, the heavy quarks can be treated non-relativistically in the hadron rest frame. This allows for the construction of reasonable QCD potential models and also makes lattice QCD calculations easier. The heavy quark hadrons have a high probability for decay to fi-

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nal states with leptons (like electrons, muons), which are easier to detect experimentally as compared to hadron detection.

The recent discovery of a tetraquark at LHC announced by the LHCb collaboration [4], is especially important, as it is the first time a tetraquark made up entirely of the heavy quarks c and $\bar{c}$. Since charm quarks and their anticharm counterparts are among the heavier types of quarks, it is also the first tetraquark to include more than two heavy quarks.

LHCb is a single-arm forward region spectrometer dedicated to heavy flavour physics. It is equipped to study the exotic states containing the heavy quarks b and c. A four-charm particle should decay through an intermediate state that involves a pair of two-charm particles, the J/Ψ particle discovered in 1974. The decay of J/Ψ particles can, in turn, be recognized by the appearance of a muon-antimuon pair that originates from a single location. Hence, the researchers searched for events where four muon tracks in a J/Ψ—pair candidate are required to originate from the same primary proton-proton collision vertex. J/Ψ particles could, however, be created through many other modes of interactions of quarks or gluons in proton-proton collisions. To be able to sift the four-charm particle decay from this background, the number of di-J/Ψ events were plotted as a function of the invariant mass of the two J/Ψ particles from the LHCb datasets from the first and second runs of the Large Hadron Collider. The tetraquark events showed up as a bump at a fixed value of the invariant mass. The bump has a statistical significance of more than five standard deviations, the usual threshold for claiming the discovery of a new particle, and it corresponds to a mass at which particles composed of four charm quarks are predicted to exist. The mass of this tetraquark is determined to be, m[X(6900)] = 6905 ±11 ± 7 MeV/c^2 and its width, Γ[X(6900)] = 80 ± 19 ± 33 MeV. The first uncertainty is statistical, and the second refers to the systemic uncertainty.

The structure of this tetraquark is still not fully unravelled. It remains to be seen, whether the new particle is really a system of four quarks tightly bound together, or a pair of two-quark particles weakly bound in a molecule-like structure or somewhere in between.

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Suggested Reading

[1] G Rajasekaran, Murray Gell-Mann (1929–2019) and the Story of Strong Interactions, *Resonance*, Vol.24, No.8, p.827–832, 2019.

[2] *Physical Review Letters*, 91, 262001: Belle Collaboration, 2003.

[3] *Physical Review Letters*, 112, 222002: LHCb Collaboration, 2014.

[4] arXiv:2006.16957v1 [hep-ex] 30 June 2020, LHCb Collaboration.

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