Recently Discovered Exotic Hadrons

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Abstract

One of the four fundamental forces in nature is the strong nuclear force. Subatomic particles called hadrons that interact via such force are bound systems of quarks and antiquarks, a particular type of elementary particle making up the Standard Model of particle physics. Ordinary hadrons contain either three quarks or a quark-antiquark pair. In the last few decades, hadrons that cannot be described as ordinary three-quark or quark-antiquark combinations have been discovered in several high-energy particle collisions. In my research, I will focus on one such non-conventional or "exotic" hadron recently observed by LHCb collaboration at CERN created in high-energy proton-proton collisions. This new hadron, called a doubly-charmed tetraquark (T_c) is composed of two charm quarks (c), an anti-up quark (u), and an anti-down quark (d). Due to the properties of the strong nuclear force described by quantum chromodynamics (QCD) each charm quark can pair with one of the anti-quarks as this pairing satisfies the requirement for color neutrality. In this case, the properties of the doubly-charmed tetraquark (T_c) can be modeled as arising from the interaction between D^+ and D^* mesons with the quark contents of cd and cu respectively. The interaction between these two mesons inside the T_c hadron can be described as giving rise to a molecular-like hadronic system in analogy to the diatomic molecules, such as HCl, bound by shared electrons. In the case of the doubly-charmed tetraquark, the residual strong force holds the two hadrons together to form a weakly bound di-hadron system, as opposed to four separate quarks in an area of space as previously thought. This model of the T_c exotic hadron serves as a non-perturbative model, allowing for a more accurate depiction compared to a time dependent Feynman diagram.

The Strong Force

The strong nuclear force can be described as the "glue" that holds protons and neutrons together, both on their own and within an atomic nucleus. Another name for the strong force is the color force. "Color," in the world of particle physics, is not the visual appearance of a quark or anti-quark. It is simply a characteristic of quarks that determines the way it interacts with other quarks, much like spin for electrons. Matter quarks can have one of three colors: red, green, or blue. Anti-quarks can be one of three anti-colors: anti-red, anti-green, or anti-blue. Composite particles, known as mesons or baryons, must be color neutral. This means that they must either contain three quarks of different colors, or a quark paired with its anti-quark, and thus, with its anti-color. The color charge of a quark is a quantum number, meaning no specific quark has a specific color. Because quarks are always found in either pairs or triplets, it is impossible to discern the color of any specific quark, as all their known configurations are color neutral.

Figure 1

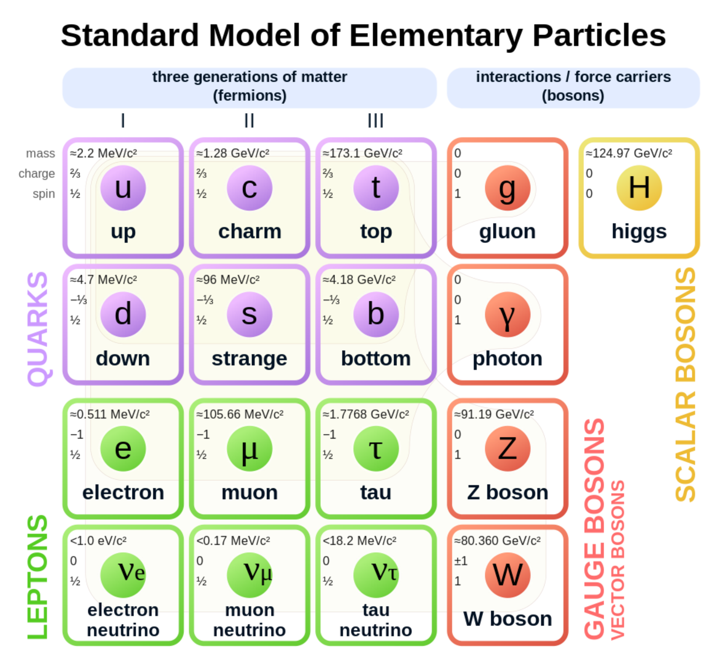
A color neutral baryon.

Note. The colors of the quarks are not specific to each particle. Own work.

The Standard Model

The Standard Model of Elementary Particles serves as a guide for the world of modern physics. The Standard Model describes three of the four fundamental forces, being the strong force, the weak force and electromagnetism. These fundamental forces are facilitated through their own carrier particles.

Figure 2
A chart showing the standard model.



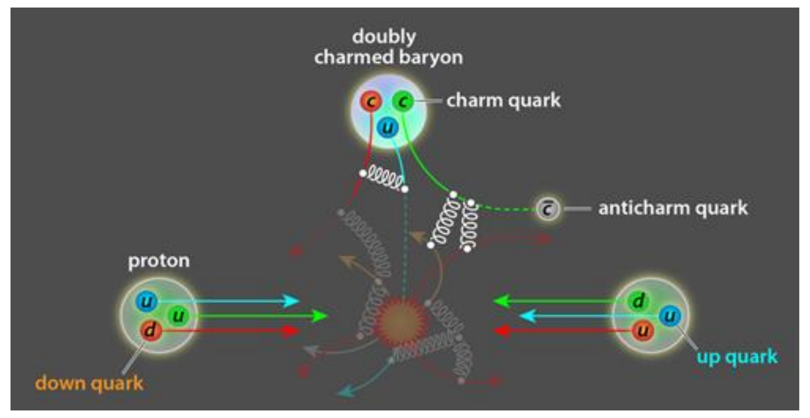
Note. From *The Standard Model* by Wikimedia Foundation.(https://en.wikipedia.org/wiki/Standard_Model)

The strong force interacts with quarks via gluons. Composite particles, such as baryons, mesons, and hadrons, are not shown in the Standard Model due to them being comprised of multiple quarks, and thus, not being considered elementary particles.

The Large Hadron Collider (LHC)

The purpose of the Large Hadron Collider is to accelerate particles to relativistic speeds, then smash them into other, similarly travelling particles. This, in turn, can form new, composite particles, such as baryons or mesons. In the case of hadronic molecules, protons are accelerated to collision, forming a doubly-charmed tetraquark particle known as a T_c exotic hadron.

Figure 3
A diagram of the proton-proton collision that produces a doubly charmed baryon, as an example of a proton-proton collision.

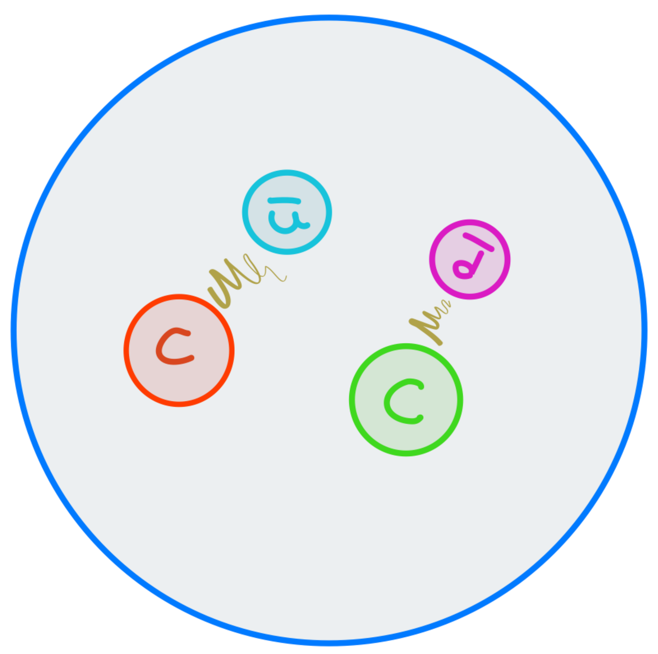


Note. From *A Doubly Charming Particle* by The American Physical Society. (https://physics.aps.org/articles/v10/100)

"Molecular-Like" Behavior

- T_c hadrons can be described as 2 charmed mesons operating under conditions similar to a covalent molecular bond
- The color force, or strong force, simulates the electromagnetic force in covalent bonds by forcing the mesons to stay color neutral, thus keeping them within the confines of the exotic hadrons. This is adjacent to molecular bonding as atomic nuclei never touch, but rather are weakly bound by the sharing of electrons.
- This is represented as the gold lines in Figure 4. The strong force is responsible for holding the mesons together, which interact subtly with each other, forming a hadronic molecule.

Figure 4
A diagram of a hadronic molecule, represented by a pair of D^+ and D^* hadrons interacting with each other through the strong force.



Note. The colors and anti-colors are not specific to either quark or anti-quark, respectively. Own work.

Conclusion

- I found that the doubly-charmed tetraquark exotic hadron can be described as a molecular system due to the strong force holding the mesons together as though they were covalently bonded.
- The strong force interaction that causes anti-down quarks to be created and annihilated mimics resonance in chemistry, as there are many quantum possibilities for what happens between a proton and a neutron, but one, main, most probable phenomenon is referred to as the "standard" progression.

Acknowledgements

Special thanks to Professor Vishwas Joshi for introducing me to the Emerging Scholars program. I would also like to thank Dr. David Weise for encouraging me and inspiring me to pursue a research project in physics. Finally, I would like to thank my parents for always supporting me, no matter how much I talk about particle physics over dinner.

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