Evidence for the Doubly Charmed Baryon Ξ_{cc}^{++} at LHCb and its Implications

Ethan Lee

April 13, 2018

Abstract

Background: Although current theories for strong interaction suggest that a baryon containing two "heavy" quarks is possible, none have been detected. **Purpose:** The detection of a baryon with two heavy quarks would benefit strong interaction theory. It would help in modeling the interactions between two heavy quarks and a light quark and increase data on quark properties such as measurements of binding energy. **Methods:** Proton-Proton collisions with a center-of-mass energy of 13 TeV and 8 TeV (a second set) were performed at LHCb. **Results:** The data collected from the two collision experiments correspond to a baryon consisting of two charm quarks and an up quark, or Ξ_{cc}^{++}. **Conclusion:** This is an expected result that supports modern quark theory but is not something that has been detected before, so it could lead to some exciting discoveries about doubly-heavy baryons.

I. Introduction

Baryons are subatomic particles made up of 3 quarks. According to quark theory, baryons can be made up of any 3 types of quarks, including multiple of the same type of quark. According to the Particle Data Group, an international group of particle physicists that collect and analyze published results related to particle physics, the "up, down, and strange quarks are considered “light”, and the charm, bottom, and top quarks are considered “heavy”. Baryons are classified into different groups based on their isospin and their quark makeup. Particles with one up or down quark are of the group Ξ and will have a subscript denoting the nature of its remaining quarks. The baryon discussed in this paper, Ξ_{cc}^{++}, is made up of one up quark and two charm quarks. Although particles containing two heavy quarks have been predicted, they have not been previously observed.

The Ξ_{cc}^{++} baryon was detected at the Large Hadron Collider beauty (LHCb) experiment [1]. As its name implies LHCb is a physics detector experiment using the Large Hadron Collider at CERN. The title beauty is because LHCb specializes in experiments involving the bottomness of a quark (another name for bottom is “beauty”).

II. Methods

Since some hadrons decay very quickly, the LHCb “detects” them by tracking the momentum of charged particles and by using Cherenkov detectors to determine a hadron’s “type”. This information, alongside other devices to measure properties during a decay, such as a calorimeter, can be used to reconstruct an event, such as the formation and decay of a Ξ_{cc}^{++} baryon, after it has happened.

The Ξ_{cc}^{++} baryon was detected using data from proton-proton collisions. More precisely, the decay mode $\Xi_{cc}^{++} \rightarrow \Lambda^+_c K^- \pi^+ \pi^+$ was detected and reconstructed using the method outlined above to determine that the Ξ_{cc}^{++} baryon had been detected. Its center-of-mass energy was measured to be 13 TeV. The Ξ_{cc}^{++} decay was reconstructed from other decay modes, namely the decay mode of baryon $\Lambda^+_c \rightarrow p K^- \pi^+$. The detection of this and three additional particles, $K^- \pi^+ \pi^+$, provides the information necessary to lead to the reconstruction of $\Xi_{cc}^{++} \rightarrow \Lambda^+_c K^- \pi^+ \pi^+$.

To reduce background noise, a multivariate selector trained with simulations of the Ξ_{cc}^{++} baryon decay cycles through the data that could represent the decay and discards candidates that do not adequately meet its simulated expectations. In the event of multiple candidates remaining after the selector has cycled through, one is randomly chosen to be the studied event. Additional checks to corroborate data selection are present, but not discussed in this paper for brevity.

III. Results

The mass of the Ξ_{cc}^{++} baryon was measured to be 3621.40 ± 1.13 MeV/c^2, where the given uncertainty is the sum of statistical and systematic uncertainties in the measurement. The statistical uncertainty is ± 0.72 MeV/c^2, and the full breakdown of systematic uncertainties can be seen in Figure 1 below. The detection of the baryon was confirmed with a second dataset with a center-of-mass energy of 8 TeV.

Source	Value [MeV/c^2]
Momentum-scale calibration	0.22
Selection bias correction	0.14
Unknown Ξ_{cc}^{++} lifetime	0.06
Mass fit model	0.07
Sum of above in quadrature	0.27
Λ_c^+ mass uncertainty	0.14

Figure 1. Systemic Uncertainty in Ξ_{cc}^{++} Experiment, from [1]

IV. Discussion

One interesting result of the measurement data taken from this experiment is that it can be compared to Ξ_{cc}^{+} data taken by SELEX (SEgmented Large-X baryon spectrometer EXperiment), an experiment run at Fermilab to study charmed baryons. The mass of Ξ_{cc}^{+} is 103 ± 2 MeV/c^2 less than the mass for Ξ_{cc}^{++}. This suggests an isospin split much, much higher than what has previously been seen in baryon systems or predicted in other papers [3][4]. This could suggest that the data collected is wrong, although this seems unlikely given the amount of additional verification steps performed. It could also suggest that the baryon detected by SELEX, Ξ_{cc}^{+}, was not accurate. Another possibility is that the papers that predicted a small isospin split were incorrect.

Observation of the Ξ_{cc}^{++} baryon could also be useful for refining strong interaction theory. Compared to quark systems of zero heavy quarks or one heavy quark, the quarks in Ξ_{cc}^{++} will likely have a different movement pattern. For example, in a three light-quark system, all three quarks have similar movement, but in a two heavy-quark system, the two heavy quarks may act like binary stars where they orbit each other, and the third light quark treats the two as a single system and orbits both. This experiment also paves the way for future experiments to search for other doubly-heavy baryons.

The binding energy between the charm quarks in Ξ_{cc}^{++} can be approximated from the mass of the baryon, as ~130 MeV [2]. Because this binding energy is so strong, it is predicted to enable quark rearrangement, an event in which two baryons with a single charm quark (Λ_c) produce the Ξ_{cc}^{++} baryon and a neutron ($\Lambda_c\Lambda_c \rightarrow \Xi_{cc}^{++}n$). The Q-value, or energy released by the reaction, is approximately 12 MeV. This leads to some interesting theories for other quark-system reactions, such as the reaction for two bottom quarks,

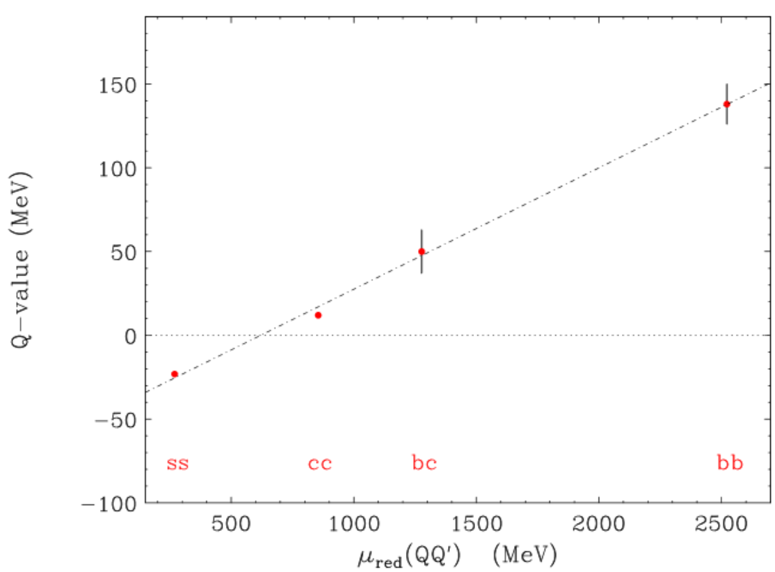

Figure 2. Q-values for Quark Reactions, from [2]

which are heavier than charm quarks. See Figure 2 for more details. The analogous reaction for bottom quark baryons, $\Lambda_b\Lambda_b \rightarrow \Xi_{bb}n$, is predicted to release energy that is approximately 140 MeV, a very high value. Large binding energies between heavy quarks are also predicted to allow for a stable bb*ud* tetraquark.

V. Conclusion

In summary, in a proton-proton collision experiment performed at LHCb, data was collected that suggests a Ξ_{cc}^{++} baryon was formed due to quark rearrangement and decayed into more stable particles. This supports prevailing quark theory and has implications suggesting that the Q value for reactions involving heavy quarks may be higher than previously thought.

VI. References:

1. R. Aaij et al. (LHCb Collaboration). Observation of the doubly charmed baryon Ξ_{cc}^{++}. Phys. Rev. Lett. 119, 112001 – Published 11 September 2017
2. Marek Karliner and Jonathan L. Rosner. Quark-level analogue of nuclear fusion with doubly-heavy baryons. Nature volume 551, pages 89–91 (02 November 2017)
3. Marek Karliner and Jonathan L. Rosner. Isospin splittings in baryons with two heavy quarks. Phys. Rev. D 96, 033004 – Published 25 August 2017
4. Chien-Wen Hwang and Ching-Ho Chung. Isospin mass splittings of heavy baryons in heavy quark symmetry. Phys. Rev. D 78, 073013 – Published 23 October 2008