GBO Proposal: Threshold Effects and Heavy Quark Symmetry in Charmed Baryon Decays

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May 20, 2003

My Ph.D. thesis concerns the application of "Effective Field Theories" on questions in particle physics. In this project, I apply a special effective theory called "Heavy Quark Effective Theory" to try and decipher observations recently made on heavy charmed baryons. This project not only gave me an opportunity to familiarize with the effective theory paradigm first-hand, but also led to a result that can easily be confirmed at current experiments. In this brief review, I will review the basic idea of heavy quark effective theory, discuss the problem I considered and present the results.

1 Heavy Quark Effective Theory

A hadron is a QCD bound state of quarks and antiquarks. What if you have a hadron with a heavy quark? It turns out that you can write down an effective theory for such an instance. In this discussion, "heavy quark" refers to either a charm or bottom quark; top quarks do not form hadrons because of their short lifetime.

To get a feeling for this "heavy quark effective theory" (HQET), consider dribbling a basketball on the ground. Conservation of energy and momentum insists that each time the ball hits the floor, the floor must recoil slightly. Therefore the Earth is recoiling against the force of the basketball bounce. Needless to say, the Earth's recoil will be negligible, and it is a perfectly valid approximation to say that the ball bounces back with all its energy intact (ignoring friction, etc.).

The analogy goes over quite well for heavy hadrons. In these particles, we have one heavy quark Q along with one (for mesons) or two (for baryons) quarks that are light (u, d or s). The light quarks together with any QCD fuzz that occurs inside the hadron are often rather off-handedly called the "light brown muck". In truth, this brown muck interacts with the heavy quark through the usual non-perturbative QCD interactions, but because the heavy quark is so much heavier than everything else, it is safe to assume that it decouples from the interactions, just like the Earth interacting with the basketball. Therefore, to a very good approximation, we can say that the heavy quark just sits there in the hadron with no special dynamics, while the light degrees of freedom interact in a mush elastically with the heavy quark.

Because the light brown muck decouples from the heavy quark, we can write down new conserved quantum numbers, specifically the quantum numbers of the light degrees of freedom. These are often denoted by an "l" for light. For example, the total angular momentum of the light brown muck (spin plus orbital) is written "J_l", and we can construct hadrons with angular momentum $J_l \otimes \frac{1}{2}$ when including the heavy quark. This is a bad approximation in general, as QCD generally prohibits you from specifying the individual quantum numbers of the quarks. However, thanks to the heavy quark approximation, this becomes a good description of heavy hadrons.

More quantum numbers means we can get a handle on the hadron spectrum as well as understand allowed decays by insisting that the HQET Lagrangian respect the light quantum numbers. Since this is only an effective theory, we know that the results that follow will not be exactly what we see, but like any effective theory we should be able to decide precisely how good these approximations are, as well as roughly what corrections appear to make the picture even more accurate. In our case, HQET can be derived from the full QCD in the limit that the heavy quark mass m_Q becomes infinite. Corrections to any results should therefore go like $\frac{1}{m_Q}$.

2 The Problem

Now that I have reviewed the philosophy of HQET, consider a specific baryon with a specific decay channel. I consider a strong isosinglet baryon with a charm quark and no strange quark; such particles are denoted by Λ_c. This particular baryon has brown muck quantum numbers $J_l^{P_l} = 1^-$ coming from additional orbital angular momentum $L_l = 1$. This additional angular momentum is denoted by a "1" subscript. The following decay is observed:

$$\Lambda_{c1}^+ \to \Lambda_c^+ \pi\pi$$

where one of the pions comes out in a P-wave to conserve angular momentum. Although this is a three-body decay, it is the most likely channel after eliminating all others by parity, isospin and spin symmetries. In addition, since the Λ_c baryon has charge $+1$, there are two channels corresponding the $\pi^+\pi^-$ and $\pi^0\pi^0$. I am especially interested in the channel with the charged pions.

It turns out that there is more to this story. The decay process likes to go through a resonance:

$$\Lambda_{c1} \to \Sigma_c\pi \to [\Lambda_c\pi]\pi$$

where the brackets are to emphasize that these are the daughter particles of the resonant Σ_c. This particle comes in charges $+2, +1, 0$; the $+2, 0$ charged resonances are for the charged pion channel, while the $+1$ resonance is for the neutral pion channel. This is now a chain of two-body decays and is favored. However, there is a subtlety in the charged pion channel.

The problem is that the mass of the $\Sigma_c\pi^\pm$ is very close to (or even slightly greater than) the mass of the Λ_{c1}; more precisely, the difference in mass between the initial and final states is smaller than the "width" of the Λ_{c1} [1]. Naively, therefore, the Σ_c resonance cannot form in the charged pion channel and the decay has to proceed through a non-resonant mode. However, even if there is a mass deficit, it can still be that the resonant decay occurs if the Σ_c is off mass shell; in other words, if the resonance does not have the proper mass. This analysis was done before in [2].

However, there is another possibility that no one had previously considered: what if the original Λ_{c1} itself was off mass shell before it decayed? Such effects could noticeably alter the results, as the usual Breit-Wigner decay amplitude will no longer be appropriate. In this analysis, my collaborators and I have recomputed the decay amplitude directly from the HQET Lagrangian, considering only the dominant decay mode.

Notice that this problem is not as bad for the neutral pion channel, as there the decay occurs roughly 7 MeV above threshold, which is much larger than the Λ_{c1} width.

3 Results

From the HQET Lagrangian we generate an energy distribution for the resonant decay of the Λ_{c1} in both the charged and neutral pion channels [1]. We find that the neutral pion channel resembles a Breit-Wigner distribution while the distribution for the charged pion channel is distorted, precisely as expected. Fitting charged pion data to a usual Breit-Wigner would therefore be expected to bias the results toward higher values for the mass. We fit our model to data taken at CLEO [3] and find that the expected mass difference[1] changes from $\Delta = (308.9 \pm 0.6)$ MeV to $\Delta = (305.6 \pm 0.3)$ MeV. The error bars decrease because our model eliminates a systematic error in the previous CLEO results since we are explicitly handling the threshold effects. In the neutral pion channel the mass has been fit to the usual Breit-Wigner in [3] and measured at $\Delta = (306.3 \pm 0.7)$ MeV. Therefore, we find that our calculation predicts a closer mass to the measured results of the neutral pion channel, and we have greatly reduced the errors. This result is a significant difference from the previously published results.

In addition, the calculation allowed us to measure a value for h_2, the HQET coupling constant mediating the decay. Our value was $h_2^2 = 0.24^{+0.23}_{-0.11}$, which is within reasonable agreement with the currently accepted value of $h_2^2 = 0.3^{+0.5}_{-0.2}$ [2].

References

[1] A. E. Blechman, et al., arXiv:hep-ph/0302040, to appear in *Phys. Rev.* **D**.

[2] P. Cho, *Phys. Rev.* **D50**, 3295 (1994); D. Pirjol and T. M. Yan, *Phys. Rev.* **D56**, 5483 (1997).

[3] Ziu Zheng, "Studies of Charmed Baryons Decaying to $\Lambda_c^+(n\pi)$", University of Florida Ph.D. Dissertation, 1999.

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[1] The convention is to subtract the mass of the "ground-state" Λ_c baryon when quoting the final results.