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$1/m_c$ Terms In Λ_c^+ Semileptonic Decays *

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We use the heavy quark effective theory to investigate the form factors that describe the semileptonic decays $\Lambda_c^+ \to \Lambda e^+ \nu$, to order $1/m_c$. We find that a total of four form factors are needed to this order, in contrast with two form factors to leading order, and six form factors in the most general case. We point out some relationships that arise among the general form factors.

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I. INTRODUCTION

The Λ_c^+ baryon is the first baryon that will offer any kind of opportunity for testing some of the many predictions of the recently developed heavy quark effective theory (HQET) [1]. However, while the scope of the predictions that can be made within the framework of this effective theory are quite profound for decays in which both the parent and daughter hadrons are heavy, it is not immediately clear that much can be said when the daughter hadron is light. Thus, measurement of $\Lambda_b \to \Lambda_c^+$ decays, for instance, could provide a very detailed probe of the predictions of HQET, but a more intriguing problem is what can be said about $\Lambda_c^+ \to \Lambda$ decays, which are much more readily available at present.

Fortunately, the simple Lorentz structure of the Λ_c^+ allows one to use HQET to count the form factors in Λ_c^+ semileptonic decays. This has been done in [2]. In addition, some observables in the nonleptonic decay $\Lambda_c^+ \to \Lambda\pi^+$ have been calculated, based on the predictions for the form factors in the semileptonic decay, and the assumption that the amplitude for the non leptonic decay can be factorized [3].

In view of the importance of the Λ_c^+ for HQET, we take a further look at its semileptonic decays to see whether anything else can be said. In particular, we incorporate next-to-leading-order terms in the $1/m_c$ expansion. We find that this is surprisingly easy to do, but leads to additional form factors. In the next section, we review our previous results for the decay $\Lambda_c^+ \to \Lambda e^+\nu$, for the sake of completeness. In section III we show how to include next-to-leading-order terms in the $1/m_c$ expansion, and briefly examine some of consequences of having included these terms, while in section IV we present our comments and conclusions.

II. LEADING ORDER FORM FACTORS

In the quark model, the Λ_c^+ baryon has the light u and d quarks in an isospin singlet; for proper quark-exchange symmetry, this pair of quarks must also be a spin singlet, so that the spin of this baryon is carried completely by the charm quark. Heavy quark symmetry allows us to classify such a state by $s_l^{\pi_l}$, the spin and parity of its light degrees of freedom, and so both the quark model and experiment tell us that in this case $s_l^{\pi_l} = 0^+$. This baryon may therefore be represented by a Dirac spinor:

$$|\Lambda_c^+(v)> \to u(v). \tag{1}$$

The baryons of the ground state octet may also be represented by a Dirac spinor.

For definiteness, let us consider decays to the Λ. We are interested in the general object

$$M = <\Lambda(p)|\bar{s}\Gamma c|\Lambda_c^+(p_0)> \tag{2}$$

For the specific case of electroweak decays, $\Gamma = \gamma_\mu(1-\gamma_5)$, and the general matrix element may be written as

$$\begin{aligned} &<\Lambda(p)|\bar{s}\gamma_\mu(1-\gamma_5)c|\Lambda_c^+(p_0)> \\ &= \bar{u}(p)\Big\{ \left[f_1(q^2)\gamma_\mu - if_2(q^2)\sigma_{\mu\nu}q^\nu + f_3(q^2)q_\mu\right] \\ &+ \left[g_1(q^2)\gamma_\mu - ig_2(q^2)\sigma_{\mu\nu}q^\nu + g_3(q^2)q_\mu\right]\gamma_5\Big\}u(p_0), \end{aligned} \tag{3}$$

where $q = p - p_0$. Alternatively, one may write this matrix element as

$$\begin{aligned} &<\Lambda(p)|\bar{s}\gamma_\mu(1-\gamma_5)c|\Lambda_c^+(p_0)> \\ &= \bar{u}(p)\Big\{ \left[\tilde{f}_1(q^2)\gamma_\mu + \tilde{f}_2 p_{0\mu} + \tilde{f}_3(q^2)p_\mu\right] \\ &+ \left[\tilde{g}_1(q^2)\gamma_\mu + \tilde{g}_2(q^2)p_{0\mu} + \tilde{g}_3(q^2)p_\mu\right]\gamma_5\Big\}u(p_0). \end{aligned} \tag{4}$$

It turns out that the second form is more useful when one looks at the terms that arise at higher order in $1/m_c$. The form factors of these two expressions are related by

$$\begin{aligned} \tilde{f}_1 &= f_1 - f_2\left(m_\Lambda + m_{\Lambda_c^+}\right), \; \tilde{f}_2 = f_2 - f_3, \; \tilde{f}_3 = f_2 + f_3, \\ \tilde{g}_1 &= g_1 + g_2\left(m_{\Lambda_c^+} - m_\Lambda\right), \; \tilde{g}_2 = g_2 - g_3, \; \tilde{g}_3 = g_2 + g_3. \end{aligned} \tag{5}$$

To leading order in HQET [1, 4], the current of eqn. (2) is modified, so that we are now interested in the object

$$\begin{aligned} M' &= <\Lambda(p)|\bar{s}\Gamma h_v^{(c)}|\Lambda_c^+(v)> \\ &= \bar{u}(p)A\Gamma u(v). \end{aligned} \tag{6}$$

A is the most general Lorentz scalar that can be constructed from the kinematic quantities we have at our disposal, and we have used HQET to write the second equality. It is easy to see that A can contain at most two terms, which we write as $A = F_1 + \not{p}F_2$. Thus, we have

$$<\Lambda(p)|\bar{s}\Gamma h_v^{(c)}|\Lambda_c^+(v)> = \bar{u}(p)\left(F_1 + \not{p}F_2\right)\Gamma u(v). \tag{7}$$

In addition, spin symmetry allows us to relate the form factors for $\Gamma = \gamma_\mu$ to those for $\Gamma = \gamma_\mu\gamma_5$, with the result that the electroweak transition current is purely left handed at the baryon level. Note that in contrast to the case when both hadrons are heavy, we do not know the normalization of either of these form factors. Nevertheless, in terms of these form factors we find that

$$f_1 = -g_1 = F_1 + \frac{m_\Lambda}{m_{\Lambda_c^+}} F_2, \quad f_2 = -g_2 = -f_3 = g_3 = \frac{1}{m_{\Lambda_c^+}} F_2, \tag{8}$$

so that $G_A = -G_V$, regardless of the unknown normalizations of F_1 and F_2.

In addition, if we assume that the amplitude for the decay $\Lambda_c^+ \to \Lambda\pi^+$ factorizes, we may write it as

$$\mathcal{M}_{\Lambda_c^+\to\Lambda\pi^+} = f_\pi \bar{u}(p)\left(A + B\gamma_5\right)u(v), \tag{9}$$

with

$$\begin{aligned} A &= F_1(m_{\Lambda_c^+} - m_\Lambda) + F_2(m_{\Lambda_c^+} + m_\Lambda - 2E_\Lambda) \\ B &= F_1(m_{\Lambda_c^+} + m_\Lambda) - F_2(m_{\Lambda_c^+} - m_\Lambda - 2E_\Lambda). \end{aligned} \tag{10}$$

In terms of these, we find that

$$\begin{aligned} \alpha &= \frac{-2ABP}{D}, \\ \gamma &= \frac{(E_\Lambda + m_\Lambda)A^2 - (E_\Lambda - m_\Lambda)B^2}{D}, \\ D &= (E_\Lambda + m_\Lambda)A^2 + (E_\Lambda - m_\Lambda)B^2. \end{aligned} \tag{11}$$

If we ignore the pion's mass, we obtain

$$\begin{aligned} A &\approx \frac{m_{\Lambda_c^+} - m_\Lambda}{m_{\Lambda_c^+}}(1 \text{ [illegible]} \\ B &\approx \frac{m_{\Lambda_c^+} + m_\Lambda}{m_{\Lambda_c^+}}(1 \text{ [illegible]} \end{aligned} \tag{12}$$

giving automatically $\alpha = -1$, $\gamma = 0$, c [illegible] of the relative sizes of the form factors F_1 and F_2. Hen [illegible] be valid for all heavy $\to$ light transitions, such as Λ_c^+ – [illegible] ven $\Lambda_b \to p\pi^0$. Experimentally measured values appear [illegible] ons [5, 6].

However, from eqn. (12), note that [illegible] es at $F_2/F_1 = \frac{m_{\Lambda_c^+}}{m_\Lambda}$, although the values of both α and [illegible] minate at this value of $r = F_2/F_1$. The complete picture reveals itself when one looks at the full forms for A and B, eqn. (10). Then we see that A and B have distinct zeroes, occuring at $F_1(m_{\Lambda_c^+} - m_\Lambda) = -F_2(m_{\Lambda_c^+} + m_\Lambda - 2E_\Lambda)$, $F_1(m_{\Lambda_c^+} + m_\Lambda) = F_2(m_{\Lambda_c^+} - m_\Lambda - 2E_\Lambda)$, respectively. This means that there are two possible zeroes in α, both occuring at values of $r = F_2/F_1$ very close to $-m_{\Lambda_c^+}/m_\Lambda$. The effect of these zeroes on α and γ is shown in fig. 1. Thus, given a curious accident in the ratio r, one could, in principle, obtain any value for α for these decays. It is perhaps somewhat fortituous that the measured values are close to the originally predicted values. On the other hand, the range of values of r within which one could obtain a value of α significantly different from -1 is so small, that one would have to have been extremely unlucky for this prediction not to have worked.

What this means is that for other heavy $\to$ light transitions, such as $\Lambda_c^+ \to n\pi^+$ and $\Lambda_b \to p\pi^0$, one can obtain any value of α, but $\alpha \approx -1$ would occur for all but a very narrow range of values of the ratio r. Put another way, a measurement of α much different from -1 for any of these decays would give a very precise handle on the ratio r, provided that one believes that the factorization assumption is valid, and that the leading order terms in the HQET expansion are sufficient for description of the decay.

III. $\frac{1}{M_C}$ CORRECTIONS

In the notation of ref. [4], the order $1/m_c$ part of the heavy quark Lagrangian is

$$\mathcal{L}' = \frac{1}{2m_c}\bar{h}_v^{(c)}\left[D^\mu(g_{\mu\nu} - v_\mu v_\nu)D^\nu + \frac{g_s}{2}\sigma^{\mu\nu}F_{\mu\nu}\right]h_v^{(c)}, \tag{13}$$

where the coefficients of the various terms are obtained from tree-level matching to the full QCD Lagrangian. In addition, tree-level matching of the local operator $\bar{s}\Gamma h_v^{(c)}$ to order $1/m_c$ leads to

$$\bar{s}\Gamma h_v^{(c)} \to \bar{s}\left[\Gamma - \frac{i}{2m_c}\Gamma\vec{\not{D}}\right]h_v^{(c)}. \tag{14}$$

We thus have many possible additional contibutions to this order. We begin by examining the local term

$$-i < \Lambda(p)|\bar{s}\bar{\Gamma}\vec{D}^\lambda h_v^{(c)}|\Lambda_c^+ >= \bar{u}(p)(a_1 + \not{p}a_2)\bar{\Gamma}u(v)M^\lambda. \tag{15}$$

where M^λ is the most general vector that can be constructed, and we have absorbed factors of $1/m$, into the definitions of the form factors a_1 and a_2. M^λ may be expressed in terms of two form factors as

$$M^{\lambda} = a_3 p^{\lambda} + a_4 v^{\lambda}, \tag{16}$$

so that we may write, for $\tilde{\Gamma} = \Gamma\gamma_\lambda$,

$$\begin{aligned} -i < \Lambda(p)|\bar{s}\Gamma \overrightarrow{D}^{\lambda} \gamma_\lambda h_v^{(c)}|\Lambda_c^+(v) > &= \bar{u}(p)(F_3 + \not{p}F_4)\Gamma\not{p}u(v) \\ &+ \bar{u}(p)(F_5 + \not{p}F_6)\Gamma\not{p}u(v). \end{aligned} \tag{17}$$

F_5 and F_6 may be absorbed into the leading order form factors F_1 and F_3, so that there are apparently two new form factors introduced by the local term to this order. If we choose $\tilde{\Gamma} = \Gamma$, then multiplying eqn. (15) by v_λ and using the equation of motion for $h_v^{(c)}$, gives $p \cdot v a_3 = -a_4$.

$$-i < \Lambda(p)|\bar{s}\Gamma \overrightarrow{D}^{\lambda} \gamma_\lambda h_v^{(c)}|\Lambda_c^+(v) > = \bar{u}(p)(F_3 + \not{p}F_4)\Gamma(\not{p} - v \cdot p)u(v). \tag{18}$$

At this point, if we could treat the s quark as heavy, we could arrive at a relationship between F_3 and F_1, and between F_4 and F_2, as has been done in the second and third papers of [7]. Since there is no justification for doing this, we exhibit F_3 and F_4 as independent form factors.

This local term introduces some right-handedness into the matrix element at the baryon level. To see this right-handedness, we note that

$$\begin{aligned} &-i < \Lambda(p)|\bar{s}\gamma_\mu(1 - \gamma_5)\overrightarrow{D}^{\lambda} \gamma_\lambda h_v^{(c)}|\Lambda_c^+(v) > \\ &= \bar{u}(p)(F_3 + \not{p}F_4)\gamma_\mu(1 + \gamma_5)(\not{p} - v \cdot p)u(v). \end{aligned} \tag{19}$$

Thus, at the baryon level, the full current will no longer be purely left-handed, and we would expect departures from the leading order predictions of $G_A = -G_V$, for instance.

The equation of motion of $h_v^{(c)}$ may be used to eliminate the $(v \cdot D)^3$ term. The D^2 term leads to a matrix element

$$\begin{aligned} &\frac{1}{2m_c} < \Lambda(p)|T\int d^4x \left(\bar{s}\Gamma h_v^{(c)}\right)(0)\left(\bar{h}_v^{(c)} D^2 h_v^{(c)}\right)(x)|\Lambda_c^+(v) > \\ &\equiv \bar{u}(p)(a_5 + \not{p}a_6)\Gamma\frac{(1 + \not{v})}{2}u(v), \end{aligned} \tag{20}$$

which simply renormalizes the leading order form factors F_1 and F_2.

This leaves the $\sigma^{\lambda\nu}$ term which is

$$\begin{aligned} &\frac{g_s}{4m_c} < \Lambda(p)|T\int d^4x \left(\bar{s}\Gamma h_v^{(c)}\right)(0)\left(\bar{h}_v^{(c)}\sigma_{\lambda\nu}F^{\lambda\nu} h_v^{(c)}\right)(x)|\Lambda_c^+(v) > \\ &= u(p)(a_7 + \not{p}a_8)\Gamma\frac{(1 + \not{v})}{2}\sigma_{\lambda\nu}u(v)M^{\lambda\nu}, \end{aligned} \tag{21}$$

where, $M^{\lambda\nu} = v_\lambda p_\nu$ is the most general tensor that can be constructed. A quick examination shows us that this term vanishes. We may therefore write the full matrix element, up to terms of order $1/m_c$ as

$$\begin{aligned} M &= < \Lambda(p)|\bar{s}\gamma_\mu(1 - \gamma_5)h_v^{(c)}|\Lambda_c^+(v) >_{1/m_c} \\ &\equiv \bar{u}(p)(F_1 + \not{p}F_2)\gamma_\mu(1 - \gamma_5)u(v) \\ &+ \frac{1}{2m_c}\bar{u}(p)(F_3 + \not{p}F_4)\gamma_\mu(1 + \gamma_5)(\not{p} - v \cdot p)u(v). \end{aligned} \tag{22}$$

At this point it may appear that the use of HQET to this order in the $1/m_c$ expansion does not lead to much of a gain since, in the general case, we needed six form factors to describe the decays in which we are interested, and we find that we now need four form factors. Nevertheless, this still represents some gain, and we should keep in mind that the effects of two of these form factors are expected to be small, as they arise at order $1/m_c$ in the HQET expansion. To illustrate this more clearly, let us write the general form factors of eqn. (3) in terms of the form factors of eqn. (22). We find

$$\begin{aligned} f_1 &= F_1 + \frac{m_\Lambda}{m_{\Lambda_c^+}}F_2 + \frac{1}{2m_c}\left[\left(m_{\Lambda_c^+} - v \cdot p\right)F_3 + \frac{q^2 + m_\Lambda(m_{\Lambda_c^+} - v \cdot p)}{m_{\Lambda_c^+}}F_4\right], \\ f_2 &= \frac{1}{m_{\Lambda_c^+}}F_2 + \frac{1}{2m_c}\left[F_3 + \frac{m_\Lambda + m_{\Lambda_c^+} - v \cdot p}{m_{\Lambda_c^+}}F_4\right], \\ f_3 &= -\frac{1}{m_{\Lambda_c^+}}F_2 + \frac{1}{2m_c}\left[F_3 + \frac{m_{\Lambda_c^+} - m_\Lambda + v \cdot p}{m_{\Lambda_c^+}}F_4\right], \\ g_1 &= -F_1 - \frac{m_\Lambda}{m_{\Lambda_c^+}}F_2 + \frac{1}{2m_c}\left[\left(m_{\Lambda_c^+} - v \cdot p\right)F_3 + \frac{m_\Lambda(m_{\Lambda_c^+} - v \cdot p) - q^2}{m_{\Lambda_c^+}}F_4\right], \\ g_2 &= -\frac{1}{m_{\Lambda_c^+}}F_2 - \frac{1}{2m_c}\left[F_3 + \frac{m_{\Lambda_c^+} - m_\Lambda + v \cdot p}{m_{\Lambda_c^+}}F_4\right], \\ g_3 &= \frac{1}{m_{\Lambda_c^+}}F_2 - \frac{1}{2m_c}\left[F_3 + \frac{m_{\Lambda_c^+} + m_\Lambda + v \cdot p}{m_{\Lambda_c^+}}F_4\right], \end{aligned} \tag{23}$$

where we have used $q = p_\Lambda - p_{\Lambda_c^+}$.

These forms suggest that there is a problem with the $1/m_c$ expansion, since some of the coefficients that are expected to be small, are not. Indeed, the coefficients of F_3 in the first and fourth of eqns. (23), are of order unity. To see that in fact there is no problem, it is more instructive to look at the relations between the form factors of eqn. (4) and those that we have obtained from HQET. These are

$$\begin{aligned}
\tilde{f}_1 &= F_1 - F_2 - \frac{m_\Lambda + v\cdot p}{2m_c}\left(F_3 + F_4\right),\\
\tilde{f}_2 &= \frac{2}{m_{\Lambda_c^+}}\left[F_2 + \frac{m_\Lambda - v\cdot p}{2m_c}F_4\right],\\
\tilde{f}_3 &= \frac{1}{m_c}\left(F_3 + F_4\right),\\
\tilde{g}_1 &= -F_1 - F_2 + \frac{m_\Lambda - v\cdot p}{2m_c}\left(F_3 - F_4\right),\\
\tilde{g}_2 &= \frac{-2}{m_{\Lambda_c^+}}\left[F_2 + \frac{m_\Lambda + v\cdot p}{2m_c}F_4\right],\\
\tilde{g}_3 &= \frac{1}{m_c}\left(F_4 - F_3\right).
\end{aligned} \tag{24}$$

We can therefore see that HQET predicts that $\tilde{f}_2$, $\tilde{g}_2$, $\tilde{f}_3$ and $\tilde{g}_3$ should be small, and that the $1/m_c$ expansion is still useful, at least to this order. In addition, the above discussion points out that the form factors of eqn. (4) are more useful than those of eqn. (3), in examining and classifying terms in HQET. It is interesting to note that deviations from the prediction $G_A = -G_V$ occur at the same order in the $1/m_c$ expansion for both the heavy $\rightarrow$ heavy ($\Lambda_b \rightarrow \Lambda_c^+$) and heavy $\rightarrow$ light ($\Lambda_c^+ \rightarrow \Lambda$) transitions. To this order, the relationship between f_1 and g_1 is

$$f_1 + g_1 = \frac{m_{\Lambda_c^+} - v\cdot p}{m_c}\left(F_3 + \frac{m_\Lambda}{m_{\Lambda_c^+}}F_4\right), \tag{25}$$

where the right hand side is expected to be a relatively small quantity.

If we apply the above results to the $\Lambda_c^+ \rightarrow \Lambda\pi^+$ transition, assuming that factorization is valid, we may again write the matrix element in the form

$$\mathcal{M}_{\Lambda_c^+\rightarrow\Lambda\pi^+} = f_\pi\,\bar{u}(p)\left(A + B\gamma_5\right)u(v), \tag{26}$$

where, in general,

$$\begin{aligned}
A &= f_1(m_{\Lambda_c^+} - m_\Lambda) + m_\pi^2 f_3,\\
B &= -g_1(m_{\Lambda_c^+} + m_\Lambda) + m_\pi^2 g_3.
\end{aligned} \tag{27}$$

The new terms will modify our previous results. If we neglect the mass of the pion ($q^2 = m_\pi^2 \approx 0$), these equations reduce to

$$\begin{aligned}
A &\approx \frac{m_{\Lambda_c^+} - m_\Lambda}{m_{\Lambda_c^+}}\left[m_{\Lambda_c^+}F_1 + m_\Lambda F_2 + \frac{1}{4m_c}\tilde{F}_3\right],\\
B &\approx \frac{m_{\Lambda_c^+} + m_\Lambda}{m_{\Lambda_c^+}}\left[m_{\Lambda_c^+}F_1 + m_\Lambda F_2 - \frac{1}{4m_c}\tilde{F}_3\right],\\
\tilde{F}_3 &= \left(m_{\Lambda_c^+}^2 - m_\Lambda^2\right)\left(m_{\Lambda_c^+}F_3 + m_\Lambda F_4\right).
\end{aligned} \tag{28}$$

These forms suggest that any value of α is now possible, so that one would expect, in general, deviations from the leading order prediction that $\alpha = -1$ and $\gamma = 0$. Recent CLEO [5] ($\alpha = -1.0^{+0.4}_{-0.0}$) and ARGUS [6] ($\alpha = -0.96 \pm 0.42$) measurements suggest that the new terms make only small net modifications to the leading order results. To be precise, the fact that $\alpha \approx -1$ tells us that, at $q^2 \approx 0$,

$$m_{\Lambda_c^+}F_3 + m_\Lambda F_4 \approx 0, \tag{29}$$

which gives another constraint on the new form factors that can be tested experimentally. Note that this is equivalent to the condition that $G_A \approx -G_V$.

IV. CONCLUSION

In this note, we have extended previous work by using HQET to count the form factors necessary for describing the semileptonic decay $\Lambda_c^+ \rightarrow \Lambda e^+\nu$, up to order $1/m_c$. We point out that these predictions are also valid for any allowed heavy $\rightarrow$ light semileptonic transition, such as $\Lambda_c^+ \rightarrow pe^+\nu$ and $\Lambda_b \rightarrow pe^-\bar{\nu}$. We have found that fewer form factors are needed, to this order in HQET, than are needed in general. This appears to imply that HQET is still useful here. In addition, one expects that two of the four form factors needed should lead to effects that are relatively small compared to the other two. Nevertheless, it will obviously require some effort on the part of experimentalists to test these predictions in any detail in Λ_c^+ semileptonic decays.

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FIGURES

FIG. 1. The polarization variables α and γ for the decay $\Lambda_c^+ \to \Lambda\pi^+$, as a function of $r = F_2/F_1$, in the region near the zeroes of A and B of eqn. (10).