Physics 4213/5213
Lecture 5 (Part 3)

1 Decay of the c-quark

Having just examined the decay of the strange quark, which makes transitions between families, this section examines the c-quark. In the case of the s-quark, the only transition it can make to a lighter quark is in a different family. This is not the case for the charm quark. Since quark decays are due to charged current interactions, that is they involve the $W^{\pm}$, the c-quark can make a transition to the s-quark, which can then make a transition to a u-quark as has already been shown.

A question still remains. If the s-quark can make a transition between families, can the charm quark make that same transition? The answer to this question is yes, but with a lower probability. Examples of these two types of transitions are:

$$D^+ \rightarrow K^- + \text{anything}$$
$$D^+ \rightarrow K^+ + \text{anything}$$

where the $D^+ = (c\bar{d})$, $K^- = (s\bar{u})$ and $K^+ = (\bar{s}u)$ The first decay mode involves a direct $c \rightarrow s$ transition; this decay occurs $\approx 24\%$ of the time. The second decay involves a $c \rightarrow d$ transition, which occurs $\approx 6\%$ of the time (see fig. 1). (From the figure note that K^- mode should be suppressed since it involves getting a $\bar{u}u$ pair from the vacuum.)

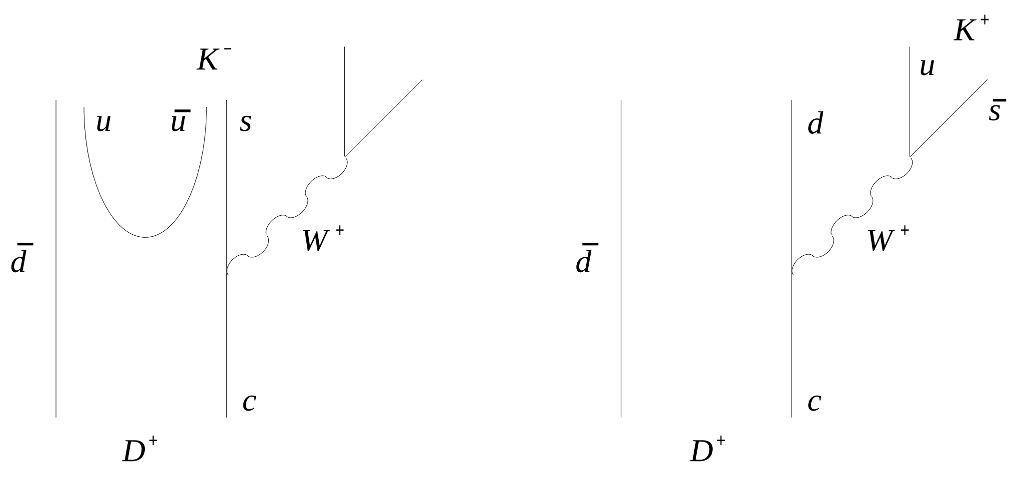

Figure 1: This show that the decay of the D^+ meson can go through either a $c \rightarrow s$ or a $c \rightarrow d$ transition.

Based on charm decays, the conclusion to draw is that if a transition can occur to other members of the same family that transition is more likely to occur.

1.1 Decay of the b-quark

Having just seen that the charm quark can make a transition to members of its own family and to members of another family with less probability, what happens to the b or t-quarks that have two lighter families that transitions can be made to. The experimental data show that transitions are most probable to members of their own family, then to the next closest family in mass and finally to family with the largest mass difference—this is counter intuitive since it would be expected that the larger the mass difference the more probable the reaction assuming no conservation laws are violated.

Based on this statement the t-quark should predominately decay through the channel $t \rightarrow W^+ + b$. Since the mass of the t-quark is significantly larger than that of the W, the W is produced as a real particle not as a virtual particle. Further, the t mass is so large, it does not have time to form a bound state before it decays. In fact the mode given above was how the t-quark was found.

2 Cabbibo Model

To explain weak decays of quarks, consider a model with only two families. Then recall that for leptons, only transitions to members in the same family are allowed. If the same condition is imposed on the quarks as on the leptons, that only transitions to members of the same family are allowed, then the weak interaction states can be considered as linear superpositions of the so-called mass states—these are the states that are defined for the strong interaction. The weak interaction states can be written as:

$$\begin{aligned} d' &= d\cos\theta_c + s\sin\theta_c \\ s' &= s\cos\theta_c - d\sin\theta_c. \end{aligned}$$

where experiment gives $\theta_c \approx 13^\circ$ and the angle is referred to as the Cabbibo angle. (The use of the trigonometric functions as the expansions coefficients, insures the proper normalization of the wave-function.) The d' and the s' are the states that are associated with the weak interaction. Therefore as an example, particles composed of an s-quark are really a linear combination of s' and d' and the fact that a transition to another family occurs is due to the fact that the weak interaction does not see the mass states (see fig. 2). As another example, particles composed of c-quarks decay to d'-quarks. But the d' is composed of s and d quarks so that either transition can occur (see fig. 3). The relative probability of either occurring is proportional to the square of the coefficient.

2.1 Cabbibo, Kobayashi and Maskawa Model

The model of Cabbibo can be expanded to three families. This is done by writing out the states in matrix form as follows:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \tag{1}$$

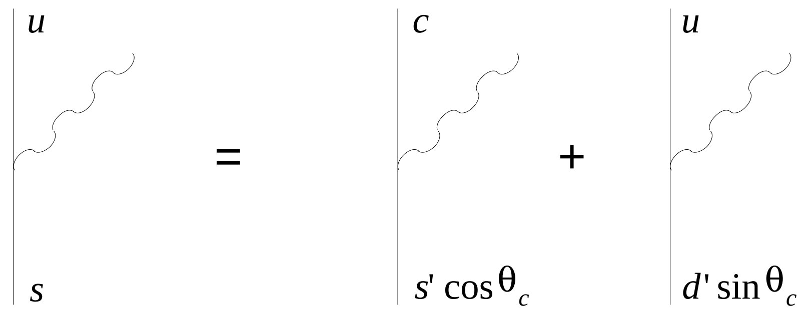

Figure 2: This shows that the decay of a strange quark, really involves the transition of the d' component to a u quark—the other component will not work due to energy conservation. The term $\sin\theta_c$ belongs with the coupling constant.

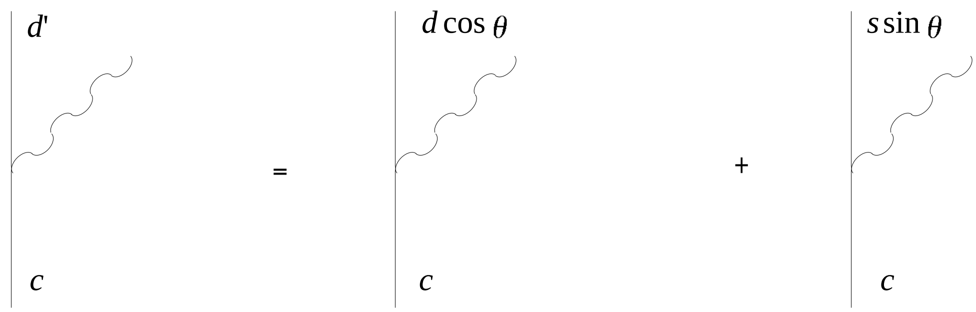

Figure 3: This set of diagrams show the possible mass states a c-quark can decay to.

The absolute magnitudes of the values of the various elements of the matrix are given by:

$$\begin{pmatrix} 0.9770 & 0.24 & 0.014 \\ 0.24 & 0.973 & 0.070 \\ 0.024 & 0.069 & 0.999 \end{pmatrix}. \tag{2}$$

These are taken as the upper limits of the values in the text. The various signs are not yet measured and the fact that the matrix has to be unitary is used to arrive at the values not measured directly. Note also that the largest probability is that the weak and mass states are equal and it decreases as the family mass difference increases.

3 Outline

1. Weak interaction (continued)
   (a) Decay of the B-meson and multi-family transitions.
   (b) The Cabbibo model.
      i. Difference between weak and mass states.
      ii. Expansion to the Kobayashi-Maskawa model.
   (c) The decay of the top-quark and its discovery.
   (d) The use of weak interactions to measure quark content.