Importance of Future Hyperon Beta Decay Experiments

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Abstract

Recent results from the KTeV experiment at Fermilab using $\Xi^0$ hyperons have enabled a great leap in improving our understanding of elementary particle physics, especially with the first form-factor measurement from the semi-leptonic decay $\Xi^0 \rightarrow \Sigma^+ e^- \bar{\nu}$. This decay is a test of whether the standard model contains all of the needed parameters to fully describe hyperon beta decay. It was observed for the first time only in 1997 even though its importance had been explicitly stated in 1961 by the early theories of the standard model as formulated by N. Cabibbo. We have the ability to improve this measurement substantially by making the definitive form-factor measurement with a sample of 30,000 such decays from a forthcoming experiment, which will either show or rule out the existence any additional second class weak currents, an obviously important measurement allowing particle physics to finally put this question to rest. We also have the ability to make a measurement of hyperon compositeness by measuring the charged $\Sigma^\pm$ beta decay into $\Lambda^0$, and in addition to search for mass coupling terms in hyperon beta decays where the muon replaces the electron, important for determining the $g_3$ and $f_3$ form-factors. These are the important questions to answer in studying strange baryon decays, and are reviewed in this article.

1 Review of the Recent KTeV Results

There are several review articles that summarize the history of hyperon beta decay [1, 2]. Here I will remind the reader of the recent important results and then in the next section elaborate on how they could be improved upon in future experiments.

The neutral beam of the KTeV experiment was produced by protons from the Fermilab Tevatron accelerator. It had two components: the rare kaon decay program, E799, and the search for direct CP violation, E832 [3]. Presented here is only a small part of the results from a neutral hyperon program that had three triggers in the E799 experiment configuration, with results from both the 1997 and 1999 runs.

Neutral $K^0$ and hyperon decays: The experiment’s fiducial decay volume, which starts 90 m downstream of the target because of the space needed to collimate the neutral beam, is where most
of the particles decay and is also the location of the sweeping magnets that eliminate the charged particles. The decay volume from 90 to 160 m from the target was at an ultrahigh vacuum to reduce interactions and had scintillator ring counters to veto those events where a particle left the fiducial volume. The spectrometer, consisting of tracking chambers, an analysis magnet, electromagnetic calorimetry (CsI) \[4\], particle identification by transition radiation detectors (TRD) \[5\], and a muon counter system with 5 m of iron filters, directly follows the decay volume. Data were collected using 16 triggers for two different experimental configurations in 1997 and 1999.

Semi-leptonic hyperon decay physics analyses accessible in KTeV are the beta decay $\Xi^0 \rightarrow \Sigma^+ e^- \bar{\nu}_e$ and muonic decay $\Xi^0 \rightarrow \Sigma^+ \mu^- \bar{\nu}_\mu$. They are important to study for their weak decay form-factors which give an understanding of their underlying structure. In the V-A formulation the transition amplitude of beta decay is

$$M = \frac{G}{\sqrt{2}} < \Sigma | J^\lambda | \Xi > \bar{u}_e \gamma_\lambda (1 + \gamma_5) u_\nu$$

(1)

The V-A hadronic current can be written as

$$< \Sigma | J^\lambda | \Xi > = \mathcal{C} i \bar{u}(\Sigma) \left[ f_1 \gamma^\lambda + f_2 \frac{\sigma^{\nu \gamma_\nu}}{M_\Xi} + f_3 q^\lambda \frac{M_e}{M_\Xi} + \right. \\
\left. \left[ g_1 \gamma^\lambda + g_2 \frac{\sigma^{\nu \gamma_\nu}}{M_\Xi} + g_3 q^\lambda \frac{M_e}{M_\Xi} \right] \gamma_5 \right] u(\Xi)$$

(2)

where $\mathcal{C}$ is the CKM matrix element and $q$ is the momentum transfer. There are 3 vector form-factors: $f_1$ (vector), $f_2$ (weak magnetism) and $f_3$ (an induced scalar); plus 3 axial-vector form-factors: $g_1$ (axial vector), $g_2$ (weak electricity) and $g_3$ (an induced pseudo-scalar). All six form-factors are real if $T$- invariance is valid. The quark model predicts a non-zero but small $g_2$ form-factor if SU(3) breaking is sizable, but the standard model assumes this term is zero. Figure 1 shows the expected changes in these observable form-factors in the standard model and various symmetry breaking schemes. The $g_3$ form-factor is expected to be large (i.e. $\frac{g_3}{g_1} \sim 8$), but it is multiplied by $\frac{M_e}{M_\Xi}$ making this term negligibly small so as not to contribute any noticeable effect. However, for the muonic decay this may no longer be assumed. Furthermore, neither of these decays had previously been observed, so measuring their branching ratio was also important as a test of the standard model, and in the case of the muon decay this could be the first place to look for a form-factor that substantially depends upon the mass of the charged lepton. The final results for the beta decay are a branching ratio of $2.60 \pm 0.11 \pm 0.16 \times 10^{-4}$, based on 626 events, where the first error is statistical and the second systematic, and the theoretical expectation is $2.6 \times 10^{-4}$. For the muonic decay a preliminary branching ratio is $3.5^{+0.9}_{-1.0} \times 10^{-6}$ based on 5 events, while the asymmetric error bars are from the small number of events and Poisson statistics at the 68% C.I. \[6\]; theoretically expected is $2.6 \times 10^{-6}$. A larger sample of these events has been obtained in the 1999 KTeV run and are shown in figure 2 right.

A very clean sample of $\Xi^0$ beta decays, figure 2 left were obtained by using the electron identification of the TRD detector. These data were used to measure the form-factor $g_2$, for which a non-zero value would indicate new physics beyond the standard model. The decay of the $\Sigma^+$ has a 98% analyzing power, and this fact makes it equivalent to a fully polarized beam. However,
spin alignment magnetics gave the ability to control this, and then to test the technique on the much larger normal-mode decay $\Xi^0 \rightarrow \Lambda^0 \pi^0$. By working in the $\Sigma^+$ reference frame, all of the form-factors could be determined by measuring the angular distribution of the proton relative to the electron neutrino (we typically use the reconstructed transverse neutrino direction) (see figure 1) or by measuring the electron energy spectrum. We can also test the technique by comparing the proton direction relative to the reconstructed $\Xi^0$. The final four form-factors are: $f_1 = 0.99 \pm 0.14$, $f_2 = 1.24 \pm 0.27$, $g_1 = 2.3 \pm 1.3$, and $g_2 = -1.4 \pm 2.1$. This analysis used the previously quoted branching ratio and permitted the $g_2$ form-factor to float. The $g_2$ value is consistent with zero and in another analysis it was constrained to be zero and the remaining form-factors re-analyzed; they remained essentially unchanged. For a more detailed description see [7].

2 Future Hyperon Beta Decay Measurements

The following is a list of the most important hyperon beta decay measurements that should be done and why, and which experiments, with no or minor modifications, may be able to perform these studies.

**CP and T violation studies with hyperons:** The subject of CP violation, first seen with the neutral $K^0$ system and hints now just emerging with the $B^0$ meson, is an important topic to extend to baryons. The first place this might be able to emerge is with hyperons that can be produced copiously. The interest in this physics topic is covered elsewhere in these proceedings [8]. However, a minor point not covered there is that a large anti-hyperon beta decay sample could be fertile
Figure 2: A very clean sample of $\Xi^0$ beta decay events from the KTeV 1997 run is shown on the left; these were used for the form-factor measurements. On the right is the sample of $\Xi^0$ muonic decays from the KTeV 1999 run, plotting the mass of $p\pi^0$ vs $\pi^+\mu^-\pi^0$; the smaller dots are Monte-Carlo simulation of $\Xi^0$ muonic decays, the circles the correct-charge-sign data, and the triangles the wrong-charge-sign data (anti-hyperon production has a 10x suppression).

ground in which to compare the branching ratio with that of regular-matter hyperon beta decay.

**High-statistics sample of hyperon beta decays:** This would permit a precision form-factor measurement which is important as a test of the standard model as well as a good means of searching for new physics not currently in the standard model. The KTeV result mentioned in section 1 from the 1997 run is the start of such a measurement because it will permit the best form-factor analysis with the $\Sigma^+$ self-analyzing power. There is a three times larger sample from the 1999 run (see figure 5) which, when merged, will offer a great improvement in the form-factor analysis. However, there is the potential for a ten-fold improvement over the full KTeV hyperon sample (1997 plus 1999 data) with a dedicated run using the $K_{short}$ target at the NA48 experiment at CERN scheduled for 2002 [12].

The term $V_{us}$ as measured with $Ke3$ decays, $K^0 \rightarrow \pi^+e^-\bar{\nu}$, and those from three hyperon beta decays do not have perfect agreement, see table 1. In principle $V_{us}$ measured from these decays should be the same, but what is actually being measured is $|f_1 V_{us}|$. However, no particle, neither meson nor baryon, has free quarks to measure $V_{us}$ directly. It is presumed that this experimentally observed discrepancy is due to the strong force potential that the quarks are in, hence the implication that the measurement with the mesons might be closer to reality, but even this is a poor approximation.

While seeing $g_2 \neq 0$ would be an indication of new physics beyond the standard model, it is difficult to observe with any present experiment. Hence the need for a dedicated experiment. It has also been noted that hints for a non-zero $g_2$ form-factor may already exist, because when
Figure 3: On the left is a plot of the \( \Xi^0 \) beta decay events of the cosine of the angle between the proton and electron in the center of mass of the \( \Sigma^+ \), and on the right is the best fit to the form-factors \( f_1 \) and \( g_1 \).

Table 1: \( V_{us} \) as determined by various hyperon beta decays, and from \( Ke3 \) meson decay.

| Decay                  | \( V_{us} \) | Uncertainty |
|------------------------|--------------|-------------|
| \( K^0 \rightarrow \pi^+ e^- \bar{\nu} \) | 0.2188       | ±0.0016     |
| \( \Lambda^0 \rightarrow p e^- \bar{\nu} \) | 0.2130       | ±0.0020     |
| \( \Sigma^- \rightarrow n e^- \bar{\nu} \) | 0.2318       | ±0.0040     |
| \( \Xi^- \rightarrow \Lambda^0 e^- \bar{\nu} \) | 0.2434       | ±0.0068     |

\( \frac{g_2}{g_1} = 0.2 \) then all of the experimental measurements of \( V_{us} \) using hyperon beta decays (see table 1) come out equal to \( 0.220 \pm 0.004 \), in agreement with the \( Ke3 \) determination \[4\]. However, there are other possible explanations to account for the discrepancy. Obviously another measurement from a fourth hyperon beta decay would be useful, as would a high-statistics measurement of any one hyperon beta decay, the best being the \( \Xi^0 \) beta decay because of the \( \Sigma^+ \) analyzing power.

\( \Lambda^0 - \Sigma^0 \) mixing: It is known that the mesons experience mixing between neutral states, and a similar mixing with \( \Lambda - \Sigma^0 \) is expected \[14\]. This can easily be tested by measuring any difference between the branching ratio of the \( \Sigma^\pm \) beta decays \( \Sigma^+ \rightarrow \Lambda^0 e^+ \bar{\nu} \) and \( \Sigma^- \rightarrow \Lambda^0 e^- \bar{\nu} \). Both of these decays are badly measured and a 2% branching ratio measurement would suffice.

Furthermore, the \( \Lambda^0 \) has a 64% analyzing power, although not 98% like the \( \Sigma^+ \rightarrow p \pi^0 \) decay used in \( \Xi^0 \) beta decay, a large sample of either one of these decays could help resolve the \( V_{us} \) discrepancy between the hyperon beta decays and that from \( Ke3 \) decays. It has also been pointed
Figure 4: A determination of $g_2$ form-factor from the clean $\Xi^0$ beta decay sample is shown along with probability contours.

out that these $\Sigma^{\pm}$ beta decays could place the best limit on SU(3) symmetry breaking since in these decays $V_{us}$ does not enter since they have just an axial-current term.

**Form-factors outside of the normal octet:** Measurements of anti-hyperon beta decays would give another test of $V_{us}$ that may explain the discrepancy with $V_{us}$ measured using mesons, which are quark anti-quark states, and this may be contributing to the discrepancy with that of hyperons. A measurement of this would also be a test of $CP$ and $T$ violation in hyperons just by comparing branching ratios at the 0.1% level, but the real interest is in the form factor similarity for anti-matter, which has never been tested.

Measurements of the form-factors outside of the octet, such as with the $\Omega^- \rightarrow \Xi^0 e^- \bar{\nu}$, or with charm-strange baryons, $\Lambda_c^{+} \rightarrow \Lambda^0 e^+ \nu$, would give another measurements of $V_{us}$ and the first measurement of $V_{cs}$ with baryons. The $\Omega^-$ beta decay could also be compared to the matrix elements predicted by SU(6). Hyperon mixing of $\Sigma^0 - \Lambda$ could also be seen here by observing its decay into $\Sigma^0 e^- \bar{\nu}$.

**Muonic hyperon decays:** The hyperon muonic decays all have poorly measured branching ratios, and we have never had a large enough sample to be used in a form-factor measurement. This could be useful in several ways. First, a tagged decay such as $\Omega^- \rightarrow \Lambda^0 K^-$ where $K^- \rightarrow \pi^- \pi^+ \pi^-$ and $\Lambda^0 \rightarrow p \mu^- \bar{\nu}$ could be of great assistance. This would help because the presence of a $K^-$ decaying into three charged pions would indicate unambiguously the presence of a $\Lambda^0$, and an experiment such as HyperCP (E871) at Fermilab has excellent muon identification to distinguish this. Other hyperon and kaon backgrounds would be eliminated leaving only the charged-pion decay to $\mu^- \bar{\nu}$ to contend with. For a branching-ratio measurement this contribution can be simulated, and if it can be eliminated by topology constraints, then a muonic decay form-factor can be extracted.
Figure 5: The KTeV 1999 run has an additional 2100 $\Xi^0$ beta decay events.

The advantage of the $\Xi^0$ muonic decay is that there are no competing two-body backgrounds that contain a $\pi^-$, hence no background from this source. As can be seen from the cleanliness of the KTeV $\Xi^0$ muonic decay, see figure 2 right, the signal is exceptionally strong and well separated from the kaon backgrounds.

The importance of measuring hyperon muonic decays is that it is the only process where the $g_3$ form factor is expected to contribute any noticeable charged-lepton mass effects [11]. Although small, $\sim 15\%$, radiative corrections are expected to be half of this value $\sim 7\%$. Nevertheless, a sample of 300 to 500 such events is expected from the NA48 special run [12]. So there is a future experimental possibility with this type of decay. Another decay that is expected to have a lot of hyperon muonic decays is the $\Omega^-$ system. Here, due to the large $Q$ value of the beta and muonic decays, the branching ratio for $\Omega^-$ is high: $\sim 1 \times 10^{-3}$. Maybe these can be extracted cleanly from the HyperCP experimental data sample for improved branching ratio measurements. Due to the high $Q$ (released energy) phase space would not restrict their branching ratio, so just a comparison of the beta and muonic decay branching ratio in this system is a first test of the form factor equivalence. A clean sample could yield an independent form-factor measurement where $g_3$ is large enough to be seen, or rule out its existence.
Conclusions

Beta decays have been a source of great physics discoveries, since the prediction of the neutrino to account for an anomalous electron energy spectrum. With hyperons they allow an independent measurement of $V_{us}$ in the standard model, and are a great place to hunt for physics beyond the standard model. They may even hold some clues to the unification of the strong nuclear force with electro-weak theory if the form-factor $g_2$ can be explicitly shown to be non-zero. This is because although they are from a weak decay, the strong force has a substantial role in the hyperons themselves. When a more massive charged lepton such as the muon replaces the electron of beta decay, this is the only place that can show the effect of the $g_3$ form-factor. All of these exciting topics makes for continued interest in studying hyperon beta decays.

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