A MEASUREMENT OF Ξ^0 BETA DECAY BY NA48/1 AND THE EXTRACTION OF V_{US}

M. JEITLER FOR THE NA48 COLLABORATION

CERN, Geneva, Switzerland;
E-mail: manfred.jeitler@cern.ch

A large sample of Ξ^0 decays was collected by the NA48/1 collaboration at the CERN SPS accelerator during a high-intensity K_S and hyperon run in 2002. Clean signals for the semileptonic decays $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$ and $\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}_\mu$ have been obtained. The measurement of the $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$ branching ratio has been used to extract V_{us}. This measurement is of special interest because recent results on V_{us}, obtained mostly from "Ke3" decays of neutral and charged kaons ($K \to \pi e \nu$), in combination with measured values for V_{ud} seemed to be in conflict with the unitarity condition of the CKM matrix.

1 Introduction

In 2002 the NA48/1 experiment at the CERN SPS accelerator took data using a high-intensity beam of neutral kaons and hyperons. The original program of the NA48 experiment, the measurement of $Re\ \epsilon'/\epsilon$ using two targets and two beams (consisting mainly of K_L^0 and K_S^0 mesons, respectively), had been completed[1] in 2001. In 2002 the upstream target was removed and the proton intensity on the downstream target, right before the final collimator and fiducial volume of the detector, was greatly increased. This allowed to study rare decays[2,3] of K_S^0 and at the same time to carry out precision studies on hyperons, which have a similar lifetime and can therefore be observed in the same fiducial volume.

By studying hyperon decays, in particular the Ξ^0 β-decay ($\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$), one can measure the element V_{us} of the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix. This has recently been of particular interest because some measurements of CKM elements seemed to contradict the condition of unitarity of the CKM matrix demanded by the Standard Model. Unitarity requires $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$. Within present experimental errors, the last term can be neglected ($|V_{ub}|^2 \approx 10^{-5}$). V_{us} has been measured mostly from so-called $Ke3$-decays of charged and neutral kaons ($K \to \pi e \nu$) while for V_{ud} there are independent measurements from free neutron decay and from nuclear β-decay. From the measurements quoted in the Review of Particle Physics[4] it appears that the sum of the squares of these matrix elements differs from unity by 2.2 sigma. An independent measurement of V_{us} is therefore of special interest.

A further point of interest in Ξ^0 β-decay is the study of the form factors appearing in the decay amplitudes of hyperon decays. Their measurement allows to look for SU(3)-breaking effects and to learn something about possible mechanisms by which this symmetry may be broken.

Another analysis of Ξ^0 data taken at NA48 concerns the decay asymmetry in $\Xi^0 \to \Lambda\gamma$. Different models of SU(3) breaking predict strongly different values for this asymmetry. A first measurement based on a small amount of data taken by NA48 in 1999 has been published[5] while the much larger data set taken in 2002 is being analyzed.

2 Beam and detector

The NA48/1 experiment (which inherited most of its apparatus from its predecessor NA48) is a fixed-target experiment at the Super Proton Synchrotron (SPS) of CERN near Geneva. 400-GeV protons from the SPS impinge on a thin beryllium target where

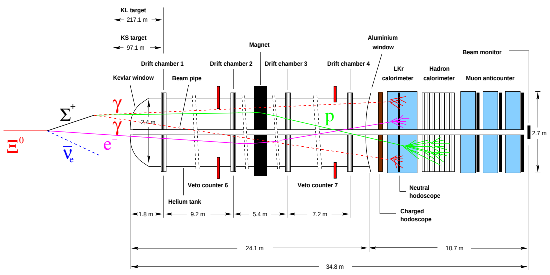

Figure 1. A Ξ^0 β-decay in the NA48/1 detector. The Ξ^0 decays into a Σ^+, an e^- and an (undetected) $\bar{\nu}_e$, and the Σ^+ subsequently decays into a proton and a π^0, which disintegrates immediately into two photons. The proton and electron are measured in the magnetic spectrometer and the hodoscope while the photons are detected in the liquid-krypton electromagnetic calorimeter.

secondary particles are produced. For the NA48/1 experiment the proton intensity was significantly increased from $3 \cdot 10^7$ protons per spill (in the original NA48 setup) to about $3 \cdot 10^{10}$ per 4.8 s spill (within a cycle of 16.2 s). Charged particles were removed by a sweeping magnet and a 5.1 m collimator, which selected a beam of neutral particles at an angle of 4.2 mrad with respect to the proton beam.

After the collimator, the neutral beam and the decay products propagate in a 89 m long vacuum tank. The neutral hyperons (Λ and Ξ^0) as well as the K_S^0 mesons decay here while most of the long-lived K_L^0 mesons and neutrons continue undecayed to a beam dump via a vacuum pipe that goes through all the downstream detectors. Ring anticounters at several positions in the vacuum tank can be used to reject decays where particles were lost to the sides of the detector.

Downstream of the vacuum tank there is a magnetic spectrometer consisting of four drift chambers and a magnet placed inside a helium-filled tank (see Fig. 1). The spatial resolution is 120 μm per view, and the momentum resolution is $\delta p/p = (0.48 \oplus 0.015\ p)\%$, with momentum p in GeV/c.

After the spectrometer there is a scintillator hodoscope for the accurate timing of charged particles (yielding a time resolution on single tracks of 250 ps) and a liquid-krypton electromagnetic calorimeter for the measurement of neutral particles with an energy resolution of $\sigma(E)/E = (3.2/\sqrt{E} \oplus 9/E \oplus 0.42)\%$ (E in GeV), followed by a hadron calorimeter and a muon detector. A more detailed description of the detector has been given elsewhere[1].

3 Data collection

The required signal for Ξ^0 β-decay (see Fig. 1) is the electron from the $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$ decay, plus a proton and two photons from the subsequent decay $\Sigma^+ \to p\pi^0$ (the other major decay mode $\Sigma^+ \to n\pi^+$ is not used).

However, by far the most frequent kinds of events in the neutral beam within the fiducial volume of the detector are K_S^0 two-body decays ($K_S^0 \to \pi^+\pi^-$ and $K_S^0 \to \pi^0\pi^0$) and Λ decays ($\Lambda \to p\pi^-$ and $\Lambda \to n\pi^0$). A very selective trigger is needed to suppress this enormous background.

The NA48/1 trigger works in three stages. The synchronous Level 1 consists of hard-wired coincidences between detectors. The trigger for the Ξ^0 β-decay requires a signal from the hodoscope, no signal from the ring anticounters, signals from the drift chambers corresponding to more than one track, and a minimum amount of energy deposited in the electromagnetic and/or the hadron calorimeter.

The Level 2 trigger works in asynchronous mode, with special fast processors using the drift chamber information. The trigger looks for two tracks giving a vertex in the fiducial region (between 100 and 5100 cm after the target), and at the first drift chamber these two tracks must be separated by more than 5 cm. The invariant mass of the tracks must not be compatible with the Λ-mass (to exclude $\Lambda \to p\pi^-$ and $\Lambda \to \bar{p}\pi^+$), and the momentum distribution of the two tracks is required to be very asymmetric to exclude $K_S^0 \to \pi^+\pi^-$ decays ($\frac{p_{bigger}}{p_{smaller}} > 3.5$, or even $\frac{p_{bigger}}{p_{smaller}} > 5$ if the invariant mass of the tracks is compatible with the K_S^0 mass).

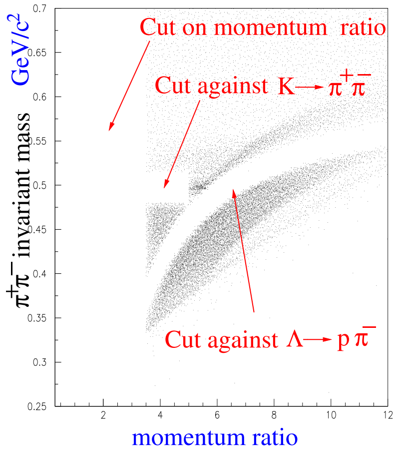

Figure 2. Trigger cuts against background from K_S^0 and Λ. The $\pi^+\pi^-$ invariant mass (under the hypothesis of a K_S^0 decay) is plotted against the ratio of track momenta.

The subsequent Level 3 trigger is implemented off line in a computer farm and carries out a full reconstruction of the event to reduce the amount of data written to tape.

For the normalization channel $\Xi^0 \to \Lambda\pi^0$ with the subsequent decay $\Lambda \to p\pi^-$ a separate trigger was set up in a similar way.

4 Data analysis

The Ξ^0 β-decay $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$ offers the great advantage that the corresponding two-body decay $\Xi^0 \to \Sigma^+\pi^-$ is excluded by energy conservation and thus constitutes no background. What makes the analysis difficult, however, is the fact that due to its high mass the proton remains very close to the beam axis and may easily be lost in the vacuum beam pipe. A very accurate knowledge of the target position and beam geometry is therefore of paramount importance, and care must be taken to compute the detector acceptance correctly. Substantial effort was spent on developing an adequate Monte Carlo program.

From the data acquired by the trigger described above, events are selected as follows. Using the two clusters produced by the decay photons of the π^0, the longitudinal distance of the π^0 (and thus the Σ^+) decay from the calorimeter is obtained as $\Delta z_{\pi^0} = \frac{1}{m_{\pi^0}}\sqrt{E_1E_2[(x_1-x_2)^2+(y_1-y_2)^2]}$. Together with the reconstructed track of the proton, this yields the decay vertex of the Σ^+ as well as its flight path. By determining the closest distance of approach with the electron track, the primary vertex of the Ξ^0-decay can be reconstructed. Due to the missing neutrino, the Ξ^0-mass cannot be reconstructed. However, as Ξ^0 β-decay is the only source of Σ^+ in the neutral beam, the events can be selected by cuts on the Σ^+ mass peak (Fig.3).

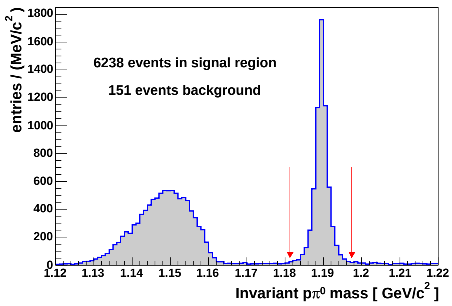

Figure 3. The $\Sigma^+ \to p\pi^0$ peak at the Σ^+ mass of 1.18 GeV/c^2. The Ξ^0 mass peak from Ξ^0 β-decay cannot be reconstructed due to the missing neutrino but as this decay is the only source of Σ^+ in the neutral beam it is reflected in the Σ^+ mass peak. The distribution to the left is due to misreconstructed $\Xi^0 \to \Lambda\pi^0$ with subsequent $\Lambda \to pe^-\bar{\nu}_e$.

To suppress background, the trigger cuts against kaon and Λ mass are refined off line, cuts are made on the geometrical acceptance of the detector (inner and outer radius, longitudinal decay volume), the detector signals are required to be in time, and the Ξ^0 and the Σ^+ vertex have to be compatible (-8 m $< z_{\Sigma^+} - z_{\Xi^0} < 40$ m). Electrons and hadrons are distinguished by comparing the momentum p measured by the spectrometer with the energy E deposited in the electromagnetic calorimeter ($E/p > 0.9$ for electrons, and < 0.8 for protons). The remaining background of about 150 events is estimated from the mass sidebands and subtracted.

In a similar way, a clear signal from about 100 events has been obtained for the muonic channel $\Xi^0 \rightarrow \Sigma^+\mu^-\bar{\nu}_\mu$. For the charge-conjugated decay $\overline{\Xi^0} \rightarrow \overline{\Sigma^+}e^+\nu_e$ around 300 events have been observed.

In the normalization channel $\Xi^0 \rightarrow \Lambda\pi^0$ all decay products are visible in the detector. The Λ vertex and track are calculated from the proton and π^- tracks, and the primary Ξ^0 vertex is then obtained from the calorimeter information on the π^0 longitudinal vertex position (as for the β-decay) and the Λ flight path.

5 Results and conclusions

The calculation of the acceptance is the major experimental challenge in Ξ^0 β-decay and the source of the dominant systematic error in our measurement. The second largest contribution to the error comes from the Level 2 trigger efficiency, which suffered from local inefficiencies in the drift chambers. These and a few other sources of systematic errors are listed in Table 1.

Table 1. Sources of systematic errors in the branching ratio measurement.

acceptance	3.2 %
trigger efficiency	2.5 %
form factors	1.0 %
Ξ^0 polarization	1.0 %
Ξ^0 life time	0.5 %

The total error on the branching ratio of the decay $\Xi^0 \rightarrow \Sigma^+e^-\bar{\nu}_e$ is dominated by systematics. Our result is

$$\mathbf{Br} = (\mathbf{2.51 \pm 0.03_{stat} \pm 0.11_{syst}}) \times \mathbf{10^{-4}}.$$

Using literature values[4] for the Ξ^0 lifetime and form factors, this yields a decay rate

$$\mathbf{\Gamma = (8.66 \pm 0.38_{exp} \pm 0.27_{lifetime}) \times 10^5 s^{-1}}.$$

Applying the formula $\Gamma = G_F^2|V_{us}|^2\frac{\Delta m^5}{60\pi^3}[(1-\frac{3}{2}\beta)(|f_1|^2+3|g_1|^2)]$ (with $\Delta m = m_{\Xi^0} - m_{\Sigma^+}$ and $\beta = \Delta m/m_{\Xi^0} = 0.095$) we obtain a CKM matrix element of

$$|\mathbf{V_{us}}| = \mathbf{0.214 \pm 0.006\ ^{+0.030}_{-0.025}}$$

where the first error is the one from the decay rate Γ and the second, much larger error, is due to the error in the formfactors. We have assumed[6] $f_1(0) = 1$ according to the Ademollo-Gatto theorem[7], which states that there are no first-order SU(3)-symmetry breaking affects, and $f_2(0) = 2.6$, which is derived from the magnetic moments of the proton and neutron under assumption of SU(3) symmetry. The third important input value is $g_1/f_1 = 1.32\ ^{+0.21}_{-0.17}\ {}_{stat} \pm 0.05_{syst}$, which has been measured experimentally[8]. First-order recoil corrections (but no q^2-dependence) and model-independent radiative corrections to the form factors have been included.

Considering the present error, our value for V_{us} is in perfect agreement with CKM unitarity. We are working to extract a much more precise value for g_1/f_1, which will allow to significantly reduce the error on V_{us}.

References

1. J.R. Batley et al., *Phys. Lett.* B **544** 1-2 (2002).
2. J.R. Batley et al., *Phys. Lett.* B **576** 1-2 (2003).
3. J.R. Batley et al., *Phys. Lett.* B **599** 3-4 (2004).
4. Particle Data Group, Review of Particle Physics, *Phys. Lett.* B **592** 1-4 (2004).
5. A. Lai et al., *Phys. Lett.* B **584** 3-4 (2004).
6. N. Cabibbo et al., *Phys. Rev. Lett.* **92** 25 (2004) and *Ann. Rev. Nucl. Part. Sci.* **53** (2003).
7. M. Ademollo and R. Gatto, *Phys. Rev. Lett.* **13** 264 (1964).
8. A. Alavi-Harati et al., *Phys. Rev. Lett.* **87** 132001 (2001).