Measurement of the branching ratio of the decay $\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}_\mu$

NA48/1 Collaboration

Cavendish Laboratory, University of Cambridge, Cambridge, CB3 0HE, United Kingdom

CERN, CH-1211 Genève 23, Switzerland

E. Goudzovski, P. Hristov, V. Kekelidze, V. Kozhuharov, L. Litov, D. Madigozhin, N. Molokanova, Yu. Potrebenikov, S. Stoynev, A. Zinchenko
Joint Institute for Nuclear Research, Dubna, Russian Federation

E. Monnier, E.C. Swallow, R. Winston
The Enrico Fermi Institute, The University of Chicago, Chicago, IL 60126, USA

R. Sacco, A. Walker
Department of Physics and Astronomy, University of Edinburgh, JCMB King's Buildings, Mayfield Road, Edinburgh, EH9 3JZ, United Kingdom

Dipartimento di Fisica dell'Università e Sezione dell'INFN di Ferrara, I-44100 Ferrara, Italy

A. Bizzeti, M. Calverti, G. Collazuol, E. Iacopini, M. Lenti, G. Ruggiero, M. Veltri
Dipartimento di Fisica dell'Università e Sezione dell'INFN di Firenze, I-50125 Firenze, Italy

Institut für Physik, Universität Mainz, D-55099 Mainz, Germany

A. Dabrowski, T. Fonseca Martin, M. Velasco
Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208-3112, USA

Dipartimento di Fisica dell'Università e Sezione dell'INFN di Pisa, I-56100 Pisa, Italy

C. Cerri, F. Costantini, R. Fantechi, L. Fiorini, S. Giudici, I. Mannelli, G. Pierazzini, M. Sozzi
Dipartimento di Fisica, Scuola Normale Superiore e Sezione dell’INFN di Pisa, I-56100 Pisa, Italy
1. Introduction

The study of hadron beta decays gives important information on the interplay between the weak interaction and hadron structure determined by the strong interaction [1]. In this framework, measurements on $\Xi^0$ semileptonic decays and on the related parameters are fundamental to further increase our knowledge on the constituents of the baryon octet. In particular, a clear evidence for the decay $\Xi^0 \rightarrow \Sigma^+ \mu^- \bar{\nu}_{\mu}$ and a measurement of its branching ratio will add one more constraint to the theoretical frameworks [2–6] built to explain the behavior of the baryon semileptonic decays.

In the present Letter the branching ratio of the semileptonic decay $\Xi^0 \rightarrow \Sigma^+ \mu^- \bar{\nu}_{\mu}$ is measured by normalizing to the analogue decay with an electron in the final state, already studied by the NA48/1 Collaboration [7]. The similar topologies of the final states of the two semileptonic decays allowed the same trigger conditions to be used for both data samples. The selection criteria are also similar between the two channels and only differ for the identification of the charged lepton and for cuts related to background.

From the 2002 data taking with a neutral kaon beam extracted from the CERN-SPS, the NA48/1 experiment observed 97 $\Xi^0 \rightarrow \Sigma^+ \mu^- \bar{\nu}_{\mu}$ candidates with a background contamination of $30.8 \pm 4.2$ events. From this sample, the BR($\Xi^0 \rightarrow \Sigma^+ \mu^- \bar{\nu}_{\mu}$) is measured to be $(2.17 \pm 0.32_{\text{stat}} \pm 0.17_{\text{syst}}) \times 10^{-8}$. © 2013 Elsevier B.V. All rights reserved.
rejection. This decay had already been observed by the KTeV Collaboration [8], with a sample of 9 events and a branching ratio measurement of $$(4.7^{+2.2}_{-1.6}) \times 10^{-6}$$.

2. Beam

The experiment was performed in 2002 at the CERN SPS accelerator and used a 400 GeV proton beam impinging on a Be target to produce a neutral beam. The spill length was 4.8 s out of a 16.2 s cycle time. The proton intensity was fairly constant during the spill with a mean of $5 \times 10^{10}$ particles per pulse.

For this measurement, only the $K_S$ target station of the NA48 double $K_S/K_L$ beam line [9] was used to produce the neutral beam. In this configuration, the $K_L$ beam was blocked and an additional sweeping magnet was installed to deflect charged particles away from the defining section of the $K_S$ collimators. To reduce the number of photons in the neutral beam originating primarily from $\pi^0$ decays, a 24 mm thick platinum absorber was placed in the beam between the target and the collimator. A pair of coaxial collimators, having a total thickness of 5.1 m, the axis of which formed an angle of 4.2 mrad to the proton beam direction, selected a beam of neutral long-lived particles ($K_S, K_L, \Lambda^0, \Sigma^0, n$ and $\gamma$).

The target position and the production angle were chosen in such a way that the beam axis was hitting the center of the electromagnetic calorimeter.

In order to minimize the interaction of the neutral beam with air, the collimator was immediately followed by a 90 m long evacuated tank terminated by a 0.3% $X_0$ thick Kevlar window. The NA48 detector was located downstream of this region.

On average, about $1.4 \times 10^4 \Sigma^0$ per spill, with an energy between 70 and 220 GeV, decayed in the fiducial decay volume.

3. Detector

The detector was designed for the measurement of $\text{Re}(\epsilon'/\epsilon)$, and a detailed description of the experimental layout is available at [9]. In the following sections a short description of the main detectors is reported.

3.1. Tracking

The detector included a spectrometer housed in a helium gas volume with two drift chambers before and two after a dipole magnet with a horizontal transverse momentum kick of 265 MeV/c. Each chamber had four views ($x, y, u, v$), each of which had two sense wire planes. The resulting space points were typically reconstructed with a resolution of $\sim 150 \mu$m in each projection. The spectrometer momentum resolution is parameterized as

$$\sigma_p/p = 0.48\% \oplus 0.015\% \times p$$

where $p$ is in GeV/c. This gave a resolution of 3 MeV/c$^2$ when reconstructing the kaon mass in $K^0 \rightarrow \pi^+\pi^-$ decays. The track time resolution was $\sim 14$ ns.

3.2. Electromagnetic calorimetry

The detection and measurement of the electromagnetic showers were achieved with a liquid krypton calorimeter (LKr), 27 radiation lengths deep, with a $\sim 2$ cm $\times$ 2 cm cell cross-section.

The energy resolution, expressing $E$ in GeV, is parameterized as [9]:

$$\sigma(E)/E = 3.2\%/\sqrt{E} \oplus 9\%/E \oplus 0.42\%.$$
Thus, the signal events were identified by requiring an invariant $p\pi^0$ mass consistent with the nominal $\Sigma^+$ mass value.

The $\Sigma^+$ decay was reconstructed using a positive charged track in the spectrometer (associated to the proton) and two clusters in the electromagnetic calorimeter (associated to the photons from $\pi^0 \to \gamma\gamma$ decay) within a time window of 2 ns. The longitudinal position of the $\Sigma^+$ decay vertex was determined using the $\pi^0$ mass constraint to calculate the distance of its decay point from the calorimeter:

$$\Delta \Sigma_{p,0} = \frac{1}{m_{\pi^0}} \sqrt{E_1 E_2 r_{12}^2}$$

where $E_1$ and $E_2$ are the measured energies of the two clusters and $r_{12}$ is the distance between the two clusters in the transverse plane. Good candidates were kept if the reconstructed $p\pi^0$ invariant mass was within 6 MeV/c$^2$ of the nominal $\Sigma^+$ mass value. The mass interval was tightened from 8 MeV/c$^2$ to 6 MeV/c$^2$ with respect to the normalization channel (see below) to reduce the higher background contamination in the muon channel.

Muon identification was achieved by requiring the presence of in-time signals from the first two planes of the muon detector ($\pm2$ ns with respect to the time measured in the charged hodoscope). In addition, to reject pions and electrons, the energy deposited in the electromagnetic calorimeter in association to the muon track was required to be less than 2.5 GeV.

The lower momentum threshold for the muon track was set to 7 GeV/c (it was 4 GeV/c for the electron channel) to reduce the background contamination and to increase the efficiency for muon reconstruction (see Section 7).

The muon momentum calculated in the $\Sigma^+$ rest frame was required to be less than 0.125 GeV/c, exploiting the fact that no contribution is expected from the signal sample above this limit. This cut was not applied in the normalization channel. Similarly, since the proton momentum in the signal sample is mostly above 54 GeV/c, this criterion was used to enhance the probability that sufficient energy is deposited in the electromagnetic and hadron calorimeters to satisfy the trigger condition $E_{ECL} > 30$ GeV. In the normalization channel the lower cut on the proton momentum was set at 40 GeV/c.

The $\Sigma^0$ decay vertex position was obtained by computing the closest distance of approach between the extrapolated $\Sigma^+$ line-of-flight and the muon track. This distance was required to be less than 4 cm. Furthermore, the deviation of the transverse $\Sigma^0$ vertex position from the nominal line-of-flight defined by a straight line going from the center of the $K_S$ target to the center of the liquid krypton calorimeter was required to be less than 3 cm.

The longitudinal position of the $\Sigma^0$ vertex was required to be at least 6.5 m downstream of the $K_S$ target, i.e. 0.5 m after the end of the final collimator and at most 40 m from the target. Similarly, the $\Sigma^+$ vertex position was required to be at least 6.5 m downstream of the target but at most 50 m from the target. The latter value was chosen larger than the upper limit for the $\Sigma^0$ vertex position to account for the lifetime of the $\Sigma^+$ particle. The longitudinal separation between the $\Sigma^0$ and $\Sigma^+$ decay vertices was required to be between $-8$ m and 40 m. The negative lower limit, tuned with Monte Carlo events, was chosen such as to take properly into account resolution effects.

The quantity $r_{\Sigma^0}^{\text{COG}}$ was defined as $r_{\Sigma^0}^{\text{COG}} = \bar{r}_i E_i / \sum_i E_i$ where $E_i$ is the energy of the detected particle and $\bar{r}_i$ the corresponding transverse position vector at the liquid krypton calorimeter position $z_{\Sigma^0}$. For a charged particle, the quantity $\bar{r}_i$ was obtained from the extrapolation to $z_{\Sigma^0}$ of the upstream segment of the associated track. For kinematical reasons, the missing transverse momentum ($p_T$) is smaller in the muon case with respect to the electron case.
The data sample for the normalization channel \( \Xi^0 \rightarrow \Sigma^0 \rightarrow \Sigma^+ e^- \tau_\mu \) consists of 6316 events with a background of \((3.4 \pm 0.7)%\).

A detailed description of the reconstruction and selection for the normalization channel is reported in [7]. For that decay, since the electron is completely absorbed in the LKr, the corresponding track was identified by requiring a ratio between the energy deposit in the LKr and the momentum measured by the spectrometer \((E/p)\) greater than 0.85 and lower than 1.15. The other differences in the selection criteria of the signal and normalization channels are described above.

6. Acceptance

The acceptance for both signal and normalization decay channels was computed using a detailed Monte Carlo program based on GEANT3 [9,10]. Particle interactions in the detector material as well as the response functions of the different detector elements were taken into account in the simulation. A detailed description of the generator of the electron channel can be found in [7]. The generator for the muon channel was modified to include the contribution from pseudo-scalar currents [11], parameterized with the form factor \( g_3 \) which, under Partially Conserved Axial Current (PCAC) hypothesis, can be extracted at \( q = 0 \) from the Goldberg–Treiman relation [12,13]:

\[
g_3(0)/f_1(0) = 2(M_{\Xi^0}/M_K^{-})^2 g_1(0)/f_1(0). \tag{2}
\]

Since the \( g_3 \) term is multiplied by \( m_{\text{lepton}}/m_{\Xi^0} \), its contribution is non-negligible for the muon case. Using the available experimental results [7,14,15] for the electron channel, the best estimates for the remaining non-vanishing form factors are

\[
f_2(q^2) / f_1(q^2) = 2.0 \pm 1.3, \quad g_1(q^2 = 0) / f_1(q^2 = 0) = 1.21 \pm 0.05. \tag{3}
\]

The central values were plugged into the Monte Carlo generator and the corresponding errors were used to evaluate the systematic error related to the acceptance calculation. Radiative corrections were not included in the generator of the muon channel. This leads to a systematic uncertainty of 1%, estimated using the Monte Carlo simulation for the electron channel with the electron mass substituted by the muon one. The acceptance for the signal \( \Xi^0 \rightarrow \Sigma^0 \rightarrow \Sigma^+ e^- \tau_\mu \) was calculated to be \((3.17 \pm 0.01)\%\), while the acceptance for the normalization \( \Xi^0 \rightarrow \Sigma^+ e^- \tau_\mu \) was \((2.49 \pm 0.01)\%\). Both quoted uncertainties originate from the statistics of the Monte Carlo samples.

7. \( \Xi^0 \rightarrow \Sigma^+ \mu^- \bar{\nu}_\mu \) branching ratio

The \( \Xi^0 \rightarrow \Sigma^+ \mu^- \bar{\nu}_\mu \) branching ratio was obtained from the background-subtracted numbers of selected events for signal and normalization, the corresponding acceptance values, the normalization branching ratio [7] and the efficiency on muon identification. These quantities are summarized in Table 1 and yield

\[
\text{BR}(\Xi^0 \rightarrow \Sigma^+ \mu^- \bar{\nu}_\mu) = (2.17 \pm 0.32_{\text{stat}} \pm 0.17_{\text{syst}}) \times 10^{-6}. \tag{4}
\]

8. Conclusion

Using data collected in 2002 with the NA48 detector at CERN, we obtain clear evidence of the decay \( \Xi^0 \rightarrow \Sigma^+ \mu^- \bar{\nu}_\mu \), with a precision on the branching ratio being significantly better than the existing published value:

\[
\text{BR}(\Xi^0 \rightarrow \Sigma^+ \mu^- \bar{\nu}_\mu) = (2.17 \pm 0.32_{\text{stat}} \pm 0.17_{\text{syst}}) \times 10^{-6}. \tag{5}
\]

This result is in good agreement with the theoretical prediction [11] and the branching ratio measured by the NA48/1 Collaboration for the electron channel [7], once the ratio of the corresponding decay amplitudes is taken into account.

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters used for the ( \text{BR}(\Xi^0 \rightarrow \Sigma^+ \mu^- \bar{\nu}_\mu) ) measurement. The numbers used for the normalization channel are taken from Ref. [7].</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Event statistics</td>
</tr>
<tr>
<td>Background</td>
</tr>
<tr>
<td>Acceptance</td>
</tr>
<tr>
<td>Muon inefficiency</td>
</tr>
<tr>
<td>Branching ratio</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sources of systematic uncertainties.</td>
</tr>
<tr>
<td>Source</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>Background</td>
</tr>
<tr>
<td>Normalization</td>
</tr>
<tr>
<td>L2 trigger efficiency</td>
</tr>
<tr>
<td>Form factors</td>
</tr>
<tr>
<td>Radiative corrections</td>
</tr>
<tr>
<td>Muon reconstruction efficiency</td>
</tr>
<tr>
<td>Total</td>
</tr>
</tbody>
</table>
Acknowledgements

It is a pleasure to thank the technical staff of the participating laboratories, universities and affiliated computing centers for their efforts in the construction of the NA48 apparatus, in the operation of the experiment, and in the processing of the data. We are grateful to J.G. Körner for the close collaboration and many useful discussions.

References