MEASUREMENTS OF HYPERON SEMILEPTONIC DECAYS

AT THE CERN SUPER PROTON SYNCHROTRON

II. THE $\Lambda \rightarrow pe\bar{\nu}$, $\Xi^- \rightarrow \Lambda e\bar{\nu}$, AND $\Xi^- \rightarrow \Sigma^0 e\bar{\nu}$ DECAY MODES

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(Submitted to Zeitschrift für Physik C)

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*) Work supported by the Bundesministerium für Forschung und Technologie, Fed. Rep. Germany.

ABSTRACT

The charged hyperon beam at the CERN Super Proton Synchrotron (SPS) has been used to collect data on semileptonic decays of Σ^- , Ξ^- , and Λ . A magnetic channel selected 100 GeV/c negatively charged particles produced in the forward direction by interaction of a 210 GeV/c proton beam on a BeO target. The Σ^- and Ξ^- hyperons were concurrently identified in a DISC Čerenkov counter, and their decay products were analysed by a magnetic spectrometer. Electron-hadron discrimination was achieved by the combined use of lead glass and lead/scintillator counters, transition radiation detectors, and a Čerenkov counter.

In this article we report results on the $\Xi \rightarrow \Lambda\pi(\Lambda \rightarrow p\bar{\nu})$, $\Xi \rightarrow \Lambda e\bar{\nu}(\Lambda \rightarrow p\pi)$, and $\Xi \rightarrow \Sigma^0 e\bar{\nu}(\Sigma^0 \rightarrow \Lambda\gamma)(\Lambda \rightarrow p\pi)$ decay modes. Samples of 7111 $\Lambda \rightarrow p\bar{\nu}$, 2608 $\Xi \rightarrow \Lambda e\bar{\nu}$, and 154 $\Xi \rightarrow \Sigma^0 e\bar{\nu}$ were used in our analysis. The branching ratio measurements gave values of $(8.57 \pm 0.36) \times 10^{-4}$, $(5.64 \pm 0.31) \times 10^{-4}$, and $(0.87 \pm 0.17) \times 10^{-4}$ for $\Lambda \rightarrow p\bar{\nu}$, $\Xi \rightarrow \Lambda e\bar{\nu}$, and $\Xi \rightarrow \Sigma^0 e\bar{\nu}$, respectively. Measurements of the Λ polarization and of the centre-of-mass distributions yield the axial vector to vector form factor ratio, $g_1/f_1 = +0.70 \pm 0.03$ for $\Lambda \rightarrow p\bar{\nu}$, and $g_1/f_1 = +0.25 \pm 0.05$ for $\Xi \rightarrow \Lambda e\bar{\nu}$. The effects of q^2 -dependence of f_1 and g_1 and of radiative corrections, the measurement of the weak magnetism term f_2 , and the effect of possible second-class current terms are discussed.

Results on the $\Sigma \rightarrow \Lambda e\bar{\nu}$ and $\Sigma \rightarrow n e\bar{\nu}$ decay modes are reported in separate articles.

1. INTRODUCTION

Baryon semileptonic decays appear to be rather well described within the framework of Cabibbo theory [1]. The matrix element M describing the decay $B \rightarrow B' e \bar{\nu}$ is given by the product of the matrix elements of the baryonic and leptonic currents,

$$M = \frac{G}{\sqrt{2}} \langle B' | J_\mu^h | B \rangle \bar{u}_e(p_e) \gamma^\mu (1 + \gamma^5) u_\nu(p_\nu) ,$$

where G is the universal weak coupling constant, p_e and p_ν are the electron and antineutrino four-momenta, and the leptonic current has the usual (V-A) structure. For the baryon term, the (V-A) structure of the underlying quark transition is hidden by the effects of the strong interactions. The matrix element of the baryon current is expressed in terms of six form factors f_i , g_i ($i = 1, 2, 3$):

$$\begin{aligned} \langle B' | J_\mu^h | B \rangle = & \bar{u}_{B'}(p') \left[f_1(q^2) \gamma^\mu + i \frac{f_2(q^2)}{M_B} \sigma^{\mu\nu} q_\nu + \frac{f_3(q^2)}{M_B} q^\mu + g_1(q^2) \gamma^\mu \gamma^5 \right. \\ & \left. + i \frac{g_2(q^2)}{M_B} \sigma^{\mu\nu} q_\nu \gamma^5 + \frac{g_3(q^2)}{M_B} q^\mu \gamma^5 \right] u_B(p) \times \begin{pmatrix} \cos \theta_C \\ \sin \theta_C \end{pmatrix} \quad \text{for } \Delta S = \begin{pmatrix} 0 \\ 1 \end{pmatrix} , \end{aligned}$$

where θ_C is the Cabibbo angle and q^2 is the four-momentum transfer squared $(p - p')^2$.

For the purposes of this paper, we shall neglect the f_3 and g_3 terms which contribute to the matrix element to the order m_e^2/M_B^2 . We assume the absence of second-class currents; therefore the form factor g_2 is equal to zero unless otherwise stated. Generalized conserved vector current (CVC) relates $f_1(0)$ and $f_2(0)$ to the electromagnetic form factors. Finally, $g_1(0)$ can be related, for each decay, to the antisymmetric and symmetric octet couplings, F and D .

Our experiment has gathered, with the same apparatus, high statistics information on $\Sigma \rightarrow \Lambda e \bar{\nu}$, $\Sigma \rightarrow n e \bar{\nu}$, $\Lambda \rightarrow p e \bar{\nu}$, and $\Xi \rightarrow \Lambda(\Sigma^0) e \bar{\nu}$. Results on the $\Sigma \rightarrow \Lambda e \bar{\nu}$ and the $\Sigma \rightarrow n e \bar{\nu}$ decays are published in separate articles [2,3]*). This paper describes a detailed study of the $\Lambda \rightarrow p e \bar{\nu}$, $\Xi \rightarrow \Lambda e \bar{\nu}$ and $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ decays. The primary

*) References 2 and 3 will be hereafter referred to as I.

aim of the experiment was to test the Cabibbo theory as stringently as possible, and a global fit to our data will be reported in a separate paper.

2. EXPERIMENTAL SET-UP AND TRIGGERS

A detailed description of the charged hyperon beam and of the apparatus (Fig. 1) can be found in I.

2.1 Hyperon identification

The data were recorded with the hyperon beam tuned to 100 GeV/c. The production angle was close to 0° , thus the incoming hyperons were unpolarized. For 10^6 negative particles (95% of them were pions) coming out of the channel per SPS cycle, the DISC identified concurrently 3500 Σ^- and 400 Ξ^- [4]. Five multiwire proportional chambers (MWPCs), two situated upstream and three downstream of the DISC, measured the direction of beam particles with an accuracy of ± 0.07 mrad (r.m.s.). Using the mean beam momentum and the measured horizontal angle, the momentum of the incoming hyperon was measured to better than 1%.

2.2 The magnetic spectrometer

As shown in Fig. 1, the magnetic spectrometer was situated at the end of the hyperon decay region, and comprised an analysing magnet with a bending power of 2.2 T·m (deflecting 100 GeV/c particles by 6.6 mrad horizontally), and two sets of four drift chambers to measure track coordinates upstream and downstream of the magnet.

Each set of chambers gave an accuracy of ± 0.07 mrad (r.m.s.) on the measurement of the projected angles. The combination of the measurement errors in the chambers, the effects of multiple scattering, and the approximations in the parametrization of the field strength of the magnet resulted in a momentum resolution of $\pm 1.5\%$ at 100 GeV/c.

2.3 Electron detection

The $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ and $\Lambda \rightarrow pe\bar{\nu}$ branching ratios are of the order of 10^{-4} to 10^{-3} . Excellent discrimination was therefore needed between hadrons and electrons to separate these decays from the dominant $\Xi \rightarrow \Lambda\pi, \Lambda \rightarrow p\pi$ decay mode. There were several electron detectors [5] in the apparatus (see Fig. 1):

- i) A lead-glass array, 17 blocks wide, 2 high, and 3 deep (along the beam direction), with a hole for the beam to pass through. Each layer of lead-glass blocks corresponded to 6 radiation lengths and $\frac{1}{3}$ of an absorption length. The blocks in the first layer were used to trigger on electrons. The lead glass provided a rejection of 1000 against $\Xi \rightarrow \Lambda\pi$ with an efficiency of 86% for electrons.
- ii) Two transition radiation detectors (XTRC and XTRM), each consisting of a lithium radiator and a MWPC filled with a Xe-CO₂ gas mixture. For XTRM, the radiator and the chamber were separated by the magnet: this allowed separation between ionization losses and X-rays from transition radiation. The combination of the two transition radiation detectors provided a rejection of 46 against $\Xi \rightarrow \Lambda\pi$ with an efficiency of 81% for electrons.
- iii) A lead/scintillator shower counter detected low-momentum electrons which were deflected beyond the lead-glass array. Additional rejection against hadrons was provided in this case by a gas Čerenkov counter, with a threshold set at 8.5 GeV/c for pions.

We have carefully and frequently calibrated the electron detectors by retuning the hyperon beam as an electron beam. Further calibrations were made using the semileptonic events themselves. In particular, the stability of the lead-glass counters was controlled throughout the experiment, and the efficiencies of both lead-glass and transition radiation detectors as a function of electron position and momentum were checked in detail.

The over-all rejection of these electron detectors was 46,000 against $\Xi \rightarrow \Lambda\pi$, with an efficiency $\epsilon_e = 0.70 \pm 0.02$ in the case of $\Lambda \rightarrow pe\bar{\nu}$ and $\Xi \rightarrow \Lambda e\bar{\nu}$ decays, where the quoted error includes residual systematic effects.

2.4 γ -ray detection

In order to study the $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ decay, it was essential to observe the γ -ray produced in the $\Sigma^0 \rightarrow \Lambda \gamma$ decay. These γ -rays were searched for in the lead-glass array and in the large-angle lead/scintillator hodoscope (Fig. 1). Most of the γ -rays reached the lead glass, where their energy was measured; of these, 90% converted in two lead plates, each 1.3 radiation lengths thick and situated in front of the lead-glass array. Each plate was followed by a large MWPC which provided a measurement of the position of the γ -ray conversion. This position determination, combined with the measurement of the $\Xi^- e^-$ vertex, yielded the direction of the γ -ray.

Both the energy and position measurements of γ -rays were calibrated using the π^0 from $\Sigma^+ \rightarrow p \pi^0$ decays. The π^0 energy-momentum deduced from the Σ^+ and proton tracks was compared to that obtained from the γ -ray measurements. Figures 2a and 2b show the distributions of the projected angular differences, and Fig. 2c that of the ratio between the two energy determinations. An important contribution to the widths of these distributions came from the uncertainty on the π^0 predicted from the Σ^+ and proton tracks.

In the case of the $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ analysis, a γ -ray was defined as a reconstructed impact point in the chambers, validated by energy deposition in the corresponding lead-glass blocks, such that at least 1 GeV was observed in the front layer and less than 12% of the total energy was deposited in the third layer. This requirement was efficient for γ -rays. However, after suppressing possible contributions from electrons, there remained a large number of spurious γ -rays, associated with the probability for the proton or the pion from $\Xi \rightarrow \Lambda \pi$ decay to interact in the lead glass. Figure 3a shows that in the case of $\Lambda \rightarrow p e \bar{\nu}$ decays where no γ -ray was expected, 30% of the events satisfied the γ -ray requirement.

The spurious γ -rays were reduced by a factor of 3, as shown in Fig. 3b, by requiring that, for the first two lead-glass layers, the ratios E_{out}/E of the energy deposited in the adjacent blocks to the energy deposited in the block facing the γ -ray coordinate be less than 0.6.

The γ -ray direction and energy were then used to reconstruct the $(\Lambda\gamma)$ effective mass as discussed in subsection 3.5.

2.5 Triggers

All semileptonic decays studied in this paper contained a Λ in the decay chain. Two counters (multiplicity and proton counters in Fig. 1) were required to trigger on events where the Λ decayed into $p\pi^-$ (or to $pe^-\bar{\nu}$) before the end of the decay region.

The leptonic trigger on $\Lambda \rightarrow pe^-\bar{\nu}$ and $\Xi \rightarrow \Lambda(\Sigma^0)e^-\bar{\nu}$ was thus divided into two parts:

- a signal from the DISC and the two counters mentioned above was required in order to trigger on a Ξ^- with a $\Lambda \rightarrow p\pi^-$ or $\Lambda \rightarrow pe^-\bar{\nu}$ in the final state.
- a signal from the first layer of lead-glass blocks or the shower counter was required in order to suppress most of the hadronic $\Xi \rightarrow \Lambda\pi$ decays. The on-line rejection obtained was a factor of 8 against $\Xi \rightarrow \Lambda\pi$ with a 100% efficiency for electrons.

In addition to these leptonic triggers, prescaled $\Xi \rightarrow \Lambda\pi$ decays were written on tape for monitoring of the acceptance and the reconstruction efficiencies and computation of the semileptonic branching ratios.

3. EVENT SELECTION

The data presented here correspond to a total flux of 10^8 Ξ^- identified by the DISC; of these, 10^7 satisfied the leptonic trigger requirements defined in subsection 2.5.

The off-line analysis started with track reconstruction and momentum measurement. The second step in the analysis was the kinematic reconstruction of the various decays and the elimination of backgrounds in the semileptonic samples.

A total of 42,360 $\Xi \rightarrow \Lambda\pi$ events were reconstructed from the prescaled hadronic sample with an efficiency of 40%. These kinematically constrained events were used to calibrate the Monte Carlo program, which was needed for simulation of the semileptonic decays.

The Monte Carlo program is described in Ref. I. In particular, detailed comparisons between the most important Monte Carlo and data distributions for $\Xi \rightarrow \Lambda\pi$ showed that the experiment was well simulated by the Monte Carlo program.

3.1 First selection of $\Lambda \rightarrow p\bar{e}\bar{\nu}$ and $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ candidates

The decays studied in this paper are:

They were characterized by a beam particle associated with one positively charged particle (the proton) and two negatively charged particles (the pion and the electron) in the final state. The minimum requirements in the off-line analysis of semileptonic triggers were therefore as follows:

- i) one charged particle was seen in the beam chambers;
- ii) three particles with the appropriate charges were reconstructed in the magnetic spectrometer;
- iii) one of the negatively charged particles satisfied the electron cuts [5], which reduced the $\Xi \rightarrow \Lambda\pi$ background to about 10% of the leptonic sample (see subsection 3.3);

At this stage, the $\Lambda \rightarrow p\bar{e}\bar{\nu}$ and $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ candidates were separated and the following cuts were applied:

- iv) the $(\Xi - \pi)$ missing mass for $\Lambda \rightarrow p\bar{e}\bar{\nu}$ was required to be within $\pm 10 \text{ MeV}/c^2$ of the Λ mass, and the $(p\pi)$ effective mass for $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ was required to be within $\pm 7 \text{ MeV}/c^2$ of the Λ mass;
- v) vertex ordering was required within errors for the $(\Xi\pi)$ and (pe) vertices in the case of $\Lambda \rightarrow p\bar{e}\bar{\nu}$, and for the (Ξe) and $(p\pi)$ vertices in the case of $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$.

3.2 Selection of final $\Lambda \rightarrow p\bar{\nu}$ and $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ samples

This section is devoted to describing the cuts applied to isolate the final samples of $\Xi \rightarrow \Lambda\pi(\Lambda \rightarrow p\bar{\nu})$ and $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}(\Lambda \rightarrow p\pi)$ candidates. These cuts were optimized to eliminate background from interactions and spurious electrons. The residual $\Xi \rightarrow \Lambda\pi$ background will be discussed in subsection 3.3 and contamination from other leptonic decays in subsection 3.4.

The background events described in this section came from two different sources. The main source of background arose from events where the Ξ^- , π^- , or p interacted in the region of the beam chambers (Fig. 1) and produced a π^0 , which in turn produced an electron either by Dalitz decay or γ -ray conversion. Most of these events contributed to the tails in the mass distributions (π^- or p interactions) or to the tails in the distributions of longitudinal and transverse momentum of the final baryon (Ξ^- interactions). These events were found to be at the level of 15% (20%) of the $\Lambda \rightarrow p\bar{\nu}$ ($\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$) sample. They were suppressed by the following kinematic cuts:

- i) the ratio of the final to initial baryon longitudinal momenta was required to be

$$p_p/p_\Lambda > 0.68 \text{ for } \Lambda \rightarrow p\bar{\nu} \text{ and } p_\Lambda/p_\Xi > 0.68 \text{ for } \Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu};$$
- ii) the transverse momentum of the final baryon relative to the initial baryon was required to be

$$(p_T)_{p/\Lambda} < 180 \text{ MeV/c for } \Lambda \rightarrow p\bar{\nu} \text{ and}$$

$$(p_T)_{\Lambda/\Xi} < 210 \text{ MeV/c for } \Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}.$$

The effect of these cuts is illustrated in Fig. 4, where the distribution of m_V^2 , the square of the missing neutrino mass, is shown for $\Lambda \rightarrow p\bar{\nu}$ and $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ candidates which satisfied the kinematic cuts, for events rejected by these kinematic cuts, and for Monte Carlo events. The majority of the rejected events were at large negative values of m_V^2 , corresponding to a large imbalance between the beam particle momentum and the sum of the charged particle momenta. The agreement between the data and the Monte Carlo was good, but the tails of the distribution

were not completely reproduced by the Monte Carlo. This effect could be due to residual interaction background. We have therefore required, in addition, a cut $m_V^2 > -0.02 \text{ GeV}^2/c^4$. The residual interaction background estimated from the tails of the m_V^2 distribution was $(2 \pm 2)\%$.

The second source of background came from $\Xi \rightarrow \Lambda\pi$ events in random coincidence with an electron emerging from the magnetic channel. The proportion of such events was about 5% of the $\Lambda \rightarrow pe\bar{\nu}$ and $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ samples, corresponding to an electron contamination in the beam of 3×10^{-3} . These electrons had momenta similar to those of electrons from hyperon decays; however, they were suppressed by requiring that the transverse momentum of the electron relative to the beam axis be $(p_T)_e > 40 \text{ MeV}/c$. In fact, such background events, although small in number, biased the $\Xi \rightarrow \Lambda e\bar{\nu}$ Dalitz plot, and in the case of $\Xi \rightarrow \Lambda e\bar{\nu}$ form factor analysis, a stronger cut $(p_T)_e > 60 \text{ MeV}/c$ was applied.

The final $\Lambda \rightarrow pe\bar{\nu}$ and $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ samples contained 7802 and 3472 events, respectively. For events in which several track combinations satisfied the final cuts, a single combination was selected, using the following criteria: the ratio E/p of the electron energy and momentum, measured in the lead glass and the magnet, respectively; the matching of the tracks in the magnet; and the quality of the vertex which produced the electron. About one third of the events had more than one combination, because of random beam pions or track duplication in the drift chambers upstream of the magnet.

The efficiency ϵ_s of these selection criteria relative to $\Xi \rightarrow \Lambda\pi(\Lambda \rightarrow p\pi)$ selection criteria was $\epsilon_s = 0.766$ for $\Lambda \rightarrow pe\bar{\nu}$ and $\epsilon_s = 0.686$ for $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$, the main losses being due to the cut on the transverse momentum of the electron $(p_T)_e$.

3.3 Residual $\Xi \rightarrow \Lambda\pi$ background

The $\Xi \rightarrow \Lambda\pi, \Lambda \rightarrow p\pi$ contamination in the final $\Lambda \rightarrow pe\bar{\nu}$ and $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ samples was estimated as shown in Figs. 5a and 5b.

Figure 5a shows the distribution of the $(p\pi)$ effective mass for the $\Lambda \rightarrow pe\bar{\nu}$ candidates, where the pion mass was assigned to the electron candidate. For events

with several possible track combinations, the combination which satisfied all $\Xi \rightarrow \Lambda\pi$ criteria and yielded the $(p\pi)$ effective mass closest to the Λ mass was chosen. In the data, 33% of the events had no track combination that satisfied the $\Xi \rightarrow \Lambda\pi$ selection criteria. These events are not represented in Fig. 5a. A higher fraction (37%) of Monte Carlo events fell into this category, because the Monte Carlo failed to reproduce all possible sources of multitrack combinations in the data.

The final $\Lambda \rightarrow p e \bar{\nu}$ data sample was well reproduced by adding to the Monte Carlo simulation a 7.5% contribution of $\Xi \rightarrow \Lambda\pi$, taken from that subsample of the data which almost satisfied the electron selection. These events were chosen to allow for possible distortions of the non-leptonic event distributions caused by imposing an "electron" condition on the pion. The final data sample thus contained 7802 events, of which 546 were $\Xi \rightarrow \Lambda\pi$ contamination. This proportion of residual hadronic contamination was consistent with that expected if the hadron rejections in the lead glass and in the transition radiation detectors were not correlated.

Figure 5b shows the $(E - \pi)$ missing mass for the $\Xi \rightarrow \Lambda\pi$ hadronic interpretation of $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ events. The data were well reproduced by a Monte Carlo simulation, which comprised a 76% contribution from $\Xi \rightarrow \Lambda e \bar{\nu}$, a 12% contribution from $\Xi \rightarrow \Sigma^0 e \bar{\nu}$, and an additional 12% contribution from $\Xi \rightarrow \Lambda\pi$ data. The $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ sample thus contained 3472 events, of which 400 were $\Xi \rightarrow \Lambda\pi$ background events.

For $\Lambda \rightarrow p e \bar{\nu}$ and $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ decays, the systematics on both branching ratio and form factor determinations, due to the residual non-leptonic events, were treated in two independent ways:

- i) as in Figs. 5a and 5b, this background was simulated using $\Xi \rightarrow \Lambda\pi$ data events, which just failed the final electron cuts;
- ii) this procedure was checked by applying a cut around the Λ mass in both cases, in order to suppress these residual background events.

3.4 Contamination from other leptonic decays

3.4.1 Ambiguous $\Lambda \rightarrow p e \bar{\nu}$, $\Xi \rightarrow \Lambda(\Sigma^0) e \bar{\nu}$ events

The similarity in topology of $\Xi \rightarrow \Lambda \pi (\Lambda \rightarrow p e \bar{\nu})$ and $\Xi \rightarrow \Lambda(\Sigma^0) e \bar{\nu} (\Lambda \rightarrow p \pi)$ decays resulted in some ambiguous events, which satisfied the final selection criteria for both samples. Fifteen such events were found, corresponding to less than 1% of the final samples. The effect of these events was therefore neglected in the form factor analysis.

3.4.2 $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ events in the $\Xi \rightarrow \Lambda e \bar{\nu}$ sample

The expected $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ proportion in the $\Xi \rightarrow \Lambda(\Sigma^0) e \bar{\nu}$ final sample defined in subsection 3.2 was of the order of 12%. For the $\Xi \rightarrow \Lambda e \bar{\nu}$ form factor analysis, this proportion was reduced to less than 3% of the total sample by applying a suitable cut on the square of the missing neutrino mass $m_{\bar{\nu}}^2$. This cut, $m_{\bar{\nu}}^2 < 0.004 \text{ GeV}^2/c^4$, accepted 90% of the $\Xi \rightarrow \Lambda e \bar{\nu}$ and rejected 61% of the $\Xi \rightarrow \Sigma^0 e \bar{\nu}$, since $m_{\bar{\nu}}^2$ measured the square of the missing $(\nu \gamma)$ mass in the case of a $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ decay. Additional rejection against $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ events was obtained, when the residual hadronic background from $\Xi \rightarrow \Lambda \pi$ was suppressed by a mass cut rejecting events with a $(\Xi - \pi)$ missing mass within $\pm 15 \text{ MeV}/c^2$ of the Λ mass, since the proportion of $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ events situated in this kinematic region was larger than for $\Xi \rightarrow \Lambda e \bar{\nu}$. After these cuts, the sample comprised 1805 $\Xi \rightarrow \Lambda e \bar{\nu}$ candidates, where the contribution from $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ and $\Xi \rightarrow \Lambda \pi$ was estimated to be less than 3%.

The systematic effects due to residual $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ events in the $\Xi \rightarrow \Lambda e \bar{\nu}$ final sample are discussed in the $\Xi \rightarrow \Lambda e \bar{\nu}$ form factor analysis (see subsection 5.2).

3.5 $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ search

The $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ events present in the $\Xi \rightarrow \Lambda(\Sigma^0) e \bar{\nu}$ sample were isolated by searching for the γ -rays emitted in the $\Sigma^0 \rightarrow \Lambda \gamma$ decay. Monte Carlo studies showed that the γ -rays were distributed in the following way:

- i) 71% of the γ -rays reached the lead-glass array. Position measurement in the chambers in front of the lead glass and energy measurement in the lead glass

allowed reconstruction of the effective ($\Lambda\gamma$) mass, which was then compared to the Σ^0 mass.

ii) 18% of the γ -rays reached the lead/scintillator hodoscope. Their energy was not measured and no kinematic reconstruction of the Σ^0 was possible. These events were not used in the $\Xi \rightarrow \Sigma^0 e\bar{\nu}$ analysis.

iii) 11% of the γ -rays were outside the acceptance of the apparatus.

The cuts defining the final $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ sample (subsection 3.2) were somewhat relaxed for this study [in particular, the cut $(p_T)_e > 40$ MeV/c was suppressed] in order to increase the $\Xi \rightarrow \Sigma^0 e\bar{\nu}$ event sample. The basic sample used thus contained $4053 \Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu} + 299 \Xi \rightarrow \Lambda\pi$ and other background events.

Two MWPCs, each preceded by 1.3 radiation lengths of lead, and the lead-glass array were used to detect γ -rays. These were selected according to the procedure described in subsection 2.4.

From their energy and direction, the ($\Lambda\gamma$) mass was then computed; its distribution is shown in Fig. 6a. When more than one γ -ray candidate was found, the combination closest to the Σ^0 mass was plotted. As shown in Fig. 6a, this method caused the background to peak around the Σ^0 mass. However, a clear Σ^0 signal appears above the background. The amount and the shape of this background were derived from spurious γ -rays found in the $\Lambda \rightarrow pe\bar{\nu}$ sample. Figure 6b shows the $\Xi \rightarrow \Sigma^0 e\bar{\nu}$ signal after background subtraction compared to a simulation of γ -ray detection in the lead glass: $\Sigma^0 \rightarrow \Lambda\gamma$ decays were generated by Monte Carlo, and the γ -ray detection losses due to pion or proton interactions were simulated using the $\Lambda \rightarrow pe\bar{\nu}$ data. With the tight lead-glass cuts described in subsection 2.4, the γ -ray detection efficiency was found to be 62%.

Table 1 shows the number of $\Xi \rightarrow \Sigma^0 e\bar{\nu}$ reconstructed events for the tight cuts used in Figs. 6a and 6b (sample 1) and for those events of sample 1 for which the ($\Lambda\gamma$) mass was within ± 20 MeV/c² of the Σ^0 mass (sample 2). The last column of Table 1 shows that the $\Xi \rightarrow \Sigma^0 e\bar{\nu}$ sample was stable when the signal-to-background ratio varied from 0.5 to 1. This ratio was improved by selecting events with

$m_V^2 > 0.004 \text{ GeV}^2/c^4$ (subsection 3.4), but, as shown in Fig. 4, the tails of m_V^2 were not well reproduced by the Monte Carlo. The sample was found to be stable within $\pm 10\%$ when the selection criteria were varied.

Sample 2 was used for branching ratio calculations. However, the signal-to-background ratio and the statistics were too low to perform a form factor analysis on this sample. In particular, the uncertainties due to background subtraction and γ -ray reconstruction efficiency were hard to estimate with the precision required for a form factor analysis.

The final leptonic samples are summarized in Table 2.

4. BRANCHING RATIO MEASUREMENTS

4.1 The $\Lambda \rightarrow pe\bar{\nu}$ branching ratio

The expression used to evaluate the ratio $R = \Gamma(\Lambda \rightarrow pe\bar{\nu})/\Gamma(\Lambda \rightarrow \text{all})$ was the following:

$$R = \frac{N_{\Lambda p} \times \epsilon_{\Lambda \rightarrow p\pi}}{N_{\Xi} \times P_{\Xi} \times \epsilon_e \times \epsilon_g \times \epsilon_r \times \epsilon_s} ;$$

- $N_{\Lambda p} = 7111 \pm 89$ was the number of background-free $\Lambda \rightarrow pe\bar{\nu}$ events;
- $N_{\Xi} = 42,360$ was the number of corresponding $\Xi \rightarrow \Lambda\pi$ events, $P_{\Xi} = 319.8$ was the $\Xi \rightarrow \Lambda\pi$ prescaling factor;
- $\epsilon_{\Lambda \rightarrow p\pi} = 0.642 \pm 0.005$ was the $\Lambda \rightarrow p\pi$ branching ratio (the $\Xi \rightarrow \Lambda\pi$ reconstructed events required a $\Lambda \rightarrow p\pi$ decay);
- $\epsilon_e = 0.669 \pm 0.020$ was the efficiency of the electron cuts, obtained from the data (see Ref. 5 and subsection 2.3). The value used for ϵ_e was lower than that quoted in subsection 2.3 in order to account for a known instrumental failure which affected a few runs. The error included residual systematic effects.
- $\epsilon_g, \epsilon_r, \epsilon_s$ were, respectively, the geometrical acceptance, reconstruction efficiency, and selection efficiency for $\Lambda \rightarrow pe\bar{\nu}$ relative to $\Lambda \rightarrow p\pi$: $\epsilon_g = 0.833$, $\epsilon_r = 0.922$, and $\epsilon_s = 0.766$. The change in shape of the density distribution

over the Dalitz plot, due to radiative corrections, was taken into account in the computation of the geometrical acceptance for $\Lambda \rightarrow p e \bar{\nu}$. This effect decreased the value of ϵ_g by 1.7%. Most of the systematic errors on these numbers dropped out since the decay configurations were similar.

The branching ratio was found to be stable when the cuts suppressing $\Xi \rightarrow \Lambda \pi$ residual background were varied. We therefore concluded that the systematic error due to this background was negligible. However, uncertainties due to residual background from interactions and tails in the data distributions not well reproduced by the Monte Carlo were estimated at $\pm 2\%$ (see subsection 3.2 and Table 2), and the Monte Carlo estimate of ϵ_g included a correction for losses due to interactions of the pion from $\Lambda \rightarrow p \pi$ which were not simulated in the Monte Carlo [interactions of the other pion or the proton were also present in the $\Xi \rightarrow \Lambda \pi (\Lambda \rightarrow p e \bar{\nu})$ decays]. This correction to ϵ_g was $+0.03 \pm 0.01$, the error being due to uncertainties in the determination of the probability of interactions, which would result in a complete loss of the $\Xi \rightarrow \Lambda \pi$ event.

The result was

$$R = (8.57 \pm 0.36) \times 10^{-4} ,$$

where the statistical error was 0.11×10^{-4} and the systematic error was dominated by the uncertainty on the electron efficiency, which was common to all decays studied in our experiment. This may have implications when our data are combined in an over-all fit.

4.2 The $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ and $\Xi \rightarrow \Lambda e \bar{\nu}$ branching ratios

In this subsection, we compute separately the $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ and $\Xi \rightarrow \Lambda e \bar{\nu}$ branching ratios. However, the combined $\Xi \rightarrow \Lambda (\Sigma^0) e \bar{\nu}$ branching ratio is also computed. In conjunction with the $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ measurement, this yields a better determination of the $\Xi \rightarrow \Lambda e \bar{\nu}$ branching ratio.

4.2.1 Determination of the $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ branching ratio

The ratio $R = \Gamma(\Xi \rightarrow \Sigma^0 e \bar{\nu}) / \Gamma(\Xi \rightarrow \Lambda(\Sigma^0) e \bar{\nu})$ was computed in the following way:

$$R = \frac{N_{\Xi\Sigma}}{N_{\Xi\Lambda\Sigma} \times \epsilon_g \times \epsilon_\gamma \times \epsilon_s \times \epsilon_e} ;$$

- $N_{\Xi\Sigma} = 154 \pm 19$ was the number of reconstructed $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ after background subtraction, as taken from Table 1 (sample 2);
- $N_{\Xi\Lambda\Sigma} = 4053 \pm 68$ was the total number of $\Xi \rightarrow \Lambda(\Sigma^0) e \bar{\nu}$ events used for the $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ search, after subtraction of $\Xi \rightarrow \Lambda\pi$ and spurious electron background (see subsection 3.5);
- ϵ_g was the product of the charged track geometrical acceptance for $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ relative to $\Xi \rightarrow \Lambda e \bar{\nu}$ and the lead-glass acceptance for γ -rays from $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ decays, $\epsilon_g = 0.635$;
- ϵ_γ was the γ -ray reconstruction efficiency, $\epsilon_\gamma = 0.62 \pm 0.06$, where the error came from the uncertainty on the Monte Carlo simulation of γ -ray detection;
- $\epsilon_s = 0.77$ was the efficiency of the cut $m_{\Lambda\gamma} = m_{\Sigma^0} \pm 20 \text{ MeV}/c^2$;
- $\epsilon_e = 0.952$ was the efficiency of the electron cuts for $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ relative to $\Xi \rightarrow \Lambda e \bar{\nu}$ (on the average, electrons from $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ had a lower momentum than those from $\Xi \rightarrow \Lambda e \bar{\nu}$).

The main contributions to the systematic error came from the uncertainty of $\pm 10\%$ on ϵ_γ , and from the uncertainty estimated at $\pm 10\%$ on the $\Xi \rightarrow \Lambda e \bar{\nu}$ background subtraction using $\Lambda \rightarrow p e \bar{\nu}$ events with spurious γ -rays. This background subtraction involved a relative normalization between the $\Lambda \rightarrow p e \bar{\nu}$ and $\Xi \rightarrow \Lambda(\Sigma^0) e \bar{\nu}$ samples, which was a very sensitive parameter of the $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ branching ratio determination. Other possible systematic effects were comparatively small. The result was therefore

$$R = (13.3 \pm 2.5) \times 10^{-2},$$

where the statistical error was 1.6×10^{-2} .

The branching ratio $R' = \Gamma(\Xi \rightarrow \Sigma^0 e \bar{\nu}) / \Gamma(\Xi \rightarrow \Lambda e \bar{\nu})$ was

$$R' = (15.4 \pm 3.3) \times 10^{-2}.$$

4.2.2 Determination of the $\Xi \rightarrow \Lambda e \bar{\nu}$ branching ratio

The $\Xi \rightarrow \Lambda e \bar{\nu}$ branching ratio was determined directly from the reduced sample of 1805 events quoted in subsection 3.4:

$$R = \frac{N_{\Xi\Lambda}}{N_{\Xi} \times P_{\Xi} \times \epsilon_e \times \epsilon_g \times \epsilon_r \times \epsilon_s};$$

- $N_{\Xi\Lambda}$ was the number of $\Xi \rightarrow \Lambda e \bar{\nu}$ events; this number was corrected for residual background from interactions, from $\Xi \rightarrow \Lambda \pi$, and from $\Xi \rightarrow \Sigma^0 e \bar{\nu}$. The uncertainty on this background was $\pm 3\%$, so $N_{\Xi\Lambda} = 1769 \pm 42 \pm 53$, including statistical and systematic errors due to background subtraction;
- $N_{\Xi} = 42,360$ was the number of corresponding $\Xi \rightarrow \Lambda \pi$ events, $P_{\Xi} = 319.8$ was the $\Xi \rightarrow \Lambda \pi$ prescaling factor;
- $\epsilon_e = 0.669 \pm 0.020$ was the electron detection efficiency (see subsection 4.1);
- $\epsilon_g, \epsilon_r, \epsilon_s$ were, respectively, the geometrical acceptance, reconstruction efficiency, and selection efficiency for $\Xi \rightarrow \Lambda e \bar{\nu}$ relative to $\Xi \rightarrow \Lambda \pi$: $\epsilon_g = 0.770$, $\epsilon_r = 0.914$, $\epsilon_s = 0.50 \pm 0.02$. The change in shape of the density distribution over the Dalitz plot, due to radiative corrections, was taken into account in the computation of the geometrical acceptance for $\Xi \rightarrow \Lambda e \bar{\nu}$. This effect decreased ϵ_g by 1.2%. ϵ_s contained the efficiency of the cut $m_V^2 < 0.004 \text{ GeV}^2/c^4$ (90%) of the kinematic cut on the $(\Xi - \pi)$ missing mass (85%), and was corrected by a factor of 0.95 ± 0.04 to take into account the excess of data in the tails of m_V^2 (Fig. 4). The result was

$$R = (5.56 \pm 0.35) \times 10^{-4}$$

where the statistical error was 0.13×10^{-4} .

4.2.3 Determination of the combined $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ branching ratio

The combined $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ branching ratio was computed using the same recipe as above. The $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ sample used was the one described in subsection 3.2, and contained $(3011 \pm 62 \pm 65)$ $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ events (see Table 2). The result was

$$R = \Gamma(\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu})/\Gamma(\Xi \rightarrow \Lambda\pi) = (6.51 \pm 0.31) \times 10^{-4},$$

where the statistical error was 0.13×10^{-4} .

4.2.4 Conclusions on $\Xi \rightarrow \Sigma^0 e\bar{\nu}$ and $\Xi \rightarrow \Lambda e\bar{\nu}$ branching ratios

We extracted the ratios $R_{\Xi\Sigma} = \Gamma(\Xi \rightarrow \Sigma^0 e\bar{\nu})/\Gamma(\Xi \rightarrow \Lambda\pi)$ and $R_{\Xi\Lambda} = \Gamma(\Xi \rightarrow \Lambda e\bar{\nu})/\Gamma(\Xi \rightarrow \Lambda\pi)$ using the combined $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ branching ratio and the partial $\Xi \rightarrow \Sigma^0 e\bar{\nu}$ branching ratio (see subsection 4.2.1). This method provided a determination of $R_{\Xi\Lambda}$ which avoided the uncertainties due to the cut on m_{ν}^2 . The results were

$$R_{\Xi\Sigma} = (0.87 \pm 0.17) \times 10^{-4}$$

$$R_{\Xi\Lambda} = (5.64 \pm 0.31) \times 10^{-4}.$$

The value $R_{\Xi\Lambda}$ was in good agreement with the value $(5.56 \pm 0.35) \times 10^{-4}$ found from the reduced $\Xi \rightarrow \Lambda e\bar{\nu}$ sample, and was used as the branching ratio result for $\Xi \rightarrow \Lambda e\bar{\nu}$.

5. DETERMINATION OF g_1/f_1

The distributions used to determine the form factor ratio g_1/f_1 involved information from the Dalitz plot and angular correlations using the measurement of the Λ polarization [6-8]. The Appendix to Ref. 2 describes in detail how these distributions were used in our analysis.

The Monte Carlo distributions, weighted with the matrix element and experimental efficiencies, were compared to the data distributions for a series of values of g_1/f_1 , and the χ^2 was calculated in each case. The Monte Carlo samples were about five times larger than the data samples.

5.1 The decay $\Xi \rightarrow \Lambda \pi (\Lambda \rightarrow p e \bar{\nu})$

In this decay, the proton kinetic energy T_p in the Λ rest frame, the electron-neutrino angular distribution $\cos \theta_{e\bar{\nu}}$, and the Dalitz plot density were the most sensitive to the absolute value of g_1/f_1 . The electron kinetic energy T_e and the Dalitz plot density were sensitive to the sign of g_1/f_1 . However, these last distributions were also sensitive to radiative corrections and external bremsstrahlung.

The best sensitivity to the sign of g_1/f_1 was obtained from the angular distributions of the Ξ^- in the Λ c.m.s., which reflected the Λ polarization $\vec{P}_\Lambda$ (see Appendix to Ref. 2). There were three such angular distributions, defined as

$$W[\cos(\vec{P}_\Lambda, \hat{\alpha})] = \frac{1}{2}(1 + A\vec{P}_\Lambda \hat{\alpha}) ,$$

$$W[\cos(\vec{P}_\Lambda, \hat{\beta})] = \frac{1}{2}(1 + B\vec{P}_\Lambda \hat{\beta}) ,$$

$$W[\cos(\vec{P}_\Lambda, \hat{n})] = \frac{1}{2}(1 + N\vec{P}_\Lambda \hat{n}) ,$$

where A, B, N were functions of the form factors, and $\hat{\alpha}, \hat{\beta}, \hat{n}$ formed an orthonormal basis in the Λ c.m.s.:

$$\hat{\alpha} = \frac{1}{\sqrt{2(1 + \cos \theta)}} (\hat{p}_e + \hat{p}_\nu) ,$$

$$\hat{\beta} = \frac{1}{\sqrt{2(1 - \cos \theta)}} (\hat{p}_e - \hat{p}_\nu) ,$$

$$\hat{n} = \frac{1}{|\sin \theta|} \hat{p}_e \times \hat{p}_\nu ;$$

$\hat{p}_e$ and $\hat{p}_\nu$ were unit vectors along the electron and neutrino directions in the Λ c.m.s., and θ was the angle between $\hat{p}_e$ and $\hat{p}_\nu$.

The Λ polarization was longitudinal and equal to the Ξ decay parameter α_{Ξ^-} . We used a value $\alpha_{\Xi^-} = -0.403 \pm 0.017$ (a recent measurement [9] yielded $\alpha_{\Xi^-} = -0.465 \pm 0.015$ which did not change our results). The Λ polarization in our measurement of the $\Lambda \rightarrow p e \bar{\nu}$ decay was about half that of previous experiments [10,11] on $\Lambda \rightarrow p e \bar{\nu}$ decay. One should note that, in the case of Refs. 10 and 11, the Λ polarization was transverse to its direction of motion. Thus the electron and

proton asymmetries were measured by simple up/down counting. In this experiment, however, the Λ polarization was longitudinal, and knowledge of the form factors was necessary in order to correct these asymmetries for acceptance effects in our apparatus (see Ref. I). We have checked that our data were completely consistent within the theoretical assumptions used for our analysis, as shown in Figs. 9 to 11 described below. In particular, the angular distribution α was weakly sensitive to the absolute value of g_1/f_1 , as shown in Fig. 7, and was therefore only used to determine the sign of g_1/f_1 .

Figure 8 shows the χ^2 distributions for the fit of T_p , $\cos \theta_{e\bar{\nu}}$, and the Dalitz plot density, and for two samples:

- Sample A was the final $\Lambda \rightarrow p e \bar{\nu}$ sample containing 7111 $\Lambda \rightarrow p e \bar{\nu}$ events, 546 $\Xi \rightarrow \Lambda \pi$, and 145 interactions, where the $\Xi \rightarrow \Lambda \pi$ events were simulated as described in subsection 3.3.
- Sample B contained the events of sample A which were outside the mass cut of $\pm 10 \text{ MeV}/c^2$ around the Λ mass. This sample contained an estimated 5790 $\Lambda \rightarrow p e \bar{\nu}$ events, 54 $\Xi \rightarrow \Lambda \pi$ events, and 120 interactions.

We obtained a value $|g_1/f_1| = 0.75 \pm 0.04$, using sample B to minimize uncertainties due to background.

Table 3 shows the values obtained for $|g_1/f_1|$ at the minima for both samples and the χ^2 per degree of freedom of the fit. The quoted errors were statistical only and the three measurements were strongly correlated. We have studied several sources of systematic errors, which included residual background from interactions and $\Xi \rightarrow \Lambda \pi$, variations of the electron cuts and the kinematic cuts, and uncertainties on the average beam momentum. The results were stable within errors, and we found no source of systematic errors which contributed significantly to the error on the measurement of $|g_1/f_1|$.

We included q^2 -dependence of the form factors according to the recipe of I, and obtained: $|g_1/f_1| = 0.70 \pm 0.03$.

Figure 9 shows the distributions of the projections T_p and T_e of the Dalitz plot and of $\cos \theta_{e\bar{\nu}}$ for data and Monte Carlo (sample B). Figure 10 shows the angular distributions α , β , n for data and Monte Carlo (sample B).

Figure 11 shows the determination of the sign of g_1/f_1 using the angular distribution α , T_e , and the Dalitz plot density for a subsample of 4303 events of sample B which satisfied a tighter cut on the transverse momentum of the electron $[(p_T)_e > 60 \text{ MeV}/c]$ in order to eliminate residual background from spurious electrons, which at the level of 1% of the events still strongly affected the χ^2 distribution of T_e . All three distributions unambiguously favoured the positive sign: therefore our final values were $g_1/f_1 = +0.75 \pm 0.04$ and, taking into account q^2 -dependence, $g_1/f_1 = +0.70 \pm 0.03$.

5.2 The decay $\Xi \rightarrow \Lambda e \bar{\nu} (\Lambda \rightarrow p \pi)$

In this case the Λ polarization was $\vec{P}_\Lambda = A\hat{\alpha} + B\hat{\beta} + N\hat{n}$, where $\hat{\alpha}$, $\hat{\beta}$, $\hat{n}$ formed an orthonormal basis in the Λ c.m.s.:

$$\hat{\alpha} = \frac{1}{\sqrt{2(1 + \cos \theta)}} (\hat{p}_e + \hat{p}_\nu) ,$$

$$\hat{\beta} = \frac{1}{\sqrt{2(1 - \cos \theta)}} (\hat{p}_e - \hat{p}_\nu) ,$$

$$\hat{n} = \frac{1}{|\sin \theta|} \hat{p}_e \times \hat{p}_\nu ;$$

$\hat{p}_e$ and $\hat{p}_\nu$ were unit vectors along the electron and neutrino directions in the Λ c.m.s.; θ was the angle between $\hat{p}_e$ and $\hat{p}_\nu$; and A , B , N were functions of the form factors.

This polarization was reflected in the angular distributions of the proton from the $\Lambda \rightarrow p \pi$ decay, which were given by

$$W[\cos(\hat{p}_p, \hat{\alpha})] = \frac{1}{2}(1 + \alpha_\Lambda A \hat{p}_p \hat{\alpha}) ,$$

$$W[\cos(\hat{p}_p, \hat{\beta})] = \frac{1}{2}(1 + \alpha_\Lambda B \hat{p}_p \hat{\beta}) ,$$

$$W[\cos(\hat{p}_p, \hat{n})] = \frac{1}{2}(1 + \alpha_\Lambda N \hat{p}_p \hat{n}) ,$$

where $\hat{p}_p$ was the proton momentum in the Λ c.m.s., and the Λ decay parameter was $\alpha_\Lambda = 0.642 \pm 0.014$.

In fact the angular distribution α was the most sensitive distribution to both the value and the sign of g_1/f_1 . The baryon kinetic energy T_Λ , the electron-neutrino angular distribution $\cos \theta_{e\bar{\nu}}$, and the Dalitz plot density in the Ξ rest-frame were sensitive to the absolute value of g_1/f_1 . Contrary to the $\Lambda \rightarrow p e \bar{\nu}$ decay, the Dalitz plot density and the electron kinetic energy T_e were only weakly sensitive to the sign of g_1/f_1 . This was due to the small value expected for g_1/f_1 .

We have mentioned in subsection 3.2 that, in the case of $\Xi \rightarrow \Lambda e \bar{\nu}$ decay, the background from spurious electrons strongly biased the form factor analysis. Therefore the $\Xi \rightarrow \Lambda e \bar{\nu}$ sample used in this analysis (sample A) contained events which satisfied a cut $(p_T)_e > 60$ MeV/c. This sample contained an estimated 1992 $\Xi \rightarrow \Lambda e \bar{\nu}$, 250 $\Xi \rightarrow \Sigma^0 e \bar{\nu}$, 300 $\Xi \rightarrow \Lambda \pi$, and 40 interactions. The $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ and $\Xi \rightarrow \Lambda \pi$ events were treated as described in Section 3.

The T_Λ and $\cos \theta_{e\bar{\nu}}$ distributions were the most sensitive to residual background from spurious electrons. This is illustrated in Table 4, where the fitted values of $|g_1/f_1|$ and the χ^2 per degree of freedom of the fit are shown for three different samples:

- Sample A, as described above, included a cut $(p_T)_e > 60$ MeV/c and contained 2582 events.
- Sample B contained 2068 events. For this sample the $\Xi \rightarrow \Lambda \pi$ and $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ residual contaminations were suppressed, as described in Section 3, to the level of 3% of the $\Xi \rightarrow \Lambda e \bar{\nu}$. In addition, the cut on $(p_T)_e$ was relaxed to $(p_T)_e > 40$ MeV/c, providing a study of the systematics due to possible remaining spurious electron background.
- Sample C contained 1395 events, satisfying a cut $(p_T)_e > 60$ MeV/c. The $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ contamination was suppressed as for sample B; however, the $\Xi \rightarrow \Lambda \pi$ contamination was further suppressed by requiring the $(\Xi - \pi)$ missing mass to be outside ± 15 MeV/c² of the Λ mass.

The three samples were strongly correlated, and Table 4 shows that the variations of the fitted values of $|g_1/f_1|$ for the T_Λ and $\cos \theta_{e\bar{\nu}}$ distributions could not be explained by statistical fluctuations. These variations were shown to be due to residual contamination from spurious electrons (see subsection 3.2). Our result was therefore based on sample C, for which the different distributions yielded consistent results, and on the angular distribution α , which was less sensitive to the cuts applied and which also provided a determination of the sign of g_1/f_1 . Figure 12 shows the χ^2 -distribution for the fit of this distribution as a function of g_1/f_1 . The result was

$$g_1/f_1 = +0.28 \pm 0.06 .$$

The value obtained after correction for q^2 -dependence was

$$g_1/f_1 = +0.25 \pm 0.05 .$$

Figures 13 and 14 show the distributions of T_Λ , T_e , $\cos \theta_{e\bar{\nu}}$, and the angular distributions α , β , n for sample B and for Monte Carlo events weighted with the measured value of g_1/f_1 .

5.3 Sensitivity to other terms in the form factor expansion

We have measured the weak magnetism term f_2 for both $\Lambda \rightarrow p e \bar{\nu}$ and $\Xi \rightarrow \Lambda e \bar{\nu}$ decays in the following way: we have taken g_1/f_1 from the results obtained in Section 5, and then varied the ratio f_2/f_1 used for the Monte Carlo events. The value which gave the best fit to the data was chosen. The Dalitz plot and the lepton spectrum were the most sensitive to this ratio f_2/f_1 , but also to radiative corrections and uncertainties on external bremsstrahlung. Those distributions were therefore not considered in the fit. The results of the other distributions were combined and are given in Table 5. They are in agreement with the values expected from CVC.

Time-reversal invariance and the absence of second-class currents were assumed in our analysis. Therefore we expect the value of $\text{Im}(f_1 g_1^*)$, as measured from the angular distribution n defined in Section 5, to be 0. Table 5 shows that our results are in agreement with time-reversal invariance.

Finally, we have measured for both $\Lambda \rightarrow p e \bar{\nu}$ and $\Xi \rightarrow \Lambda e \bar{\nu}$ decays the dependence of our measurement of g_1/f_1 upon the value used for g_2/f_1 (the standard value used in our analysis was $g_2 = 0$). The results were

$$g_1/f_1 = (0.70 \pm 0.03) + 0.20 g_2/f_1 \quad \text{for } \Lambda \rightarrow p e \bar{\nu} ,$$

$$g_1/f_1 = (0.25 \pm 0.05) + 0.15 g_2/f_1 \quad \text{for } \Xi \rightarrow \Lambda e \bar{\nu} .$$

Note that a value $g_2/g_1 \sim 20\%$, which is the level of SU(3) symmetry-breaking in the masses for the baryon octet, changes our measurement of g_1/f_1 by less than one standard deviation.

6. DISCUSSION AND CONCLUSIONS

The effects of radiative corrections [12] have been studied in our analysis. They will be discussed in the forthcoming paper describing a global Cabibbo fit to all our data.

6.1 Comparison with previous experiments

Table 6 shows our results compared to those of previous experiments [10,11,13-16]. The numbers quoted in Table 6 for this experiment do not include q^2 -dependence of the form factors f_1 and g_1 , nor radiative corrections. Although these effects were taken into account in our analysis, we have omitted them from our results in Table 6 for the sake of comparison.

For the first time we have provided a measurement of the $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ branching ratio and of the ratio g_1/f_1 for $\Xi \rightarrow \Lambda e \bar{\nu}$ decay. We have also improved the statistics by a factor of 100 for the measurement of the $\Xi \rightarrow \Lambda e \bar{\nu}$ branching ratio.

Our results for $\Lambda \rightarrow p e \bar{\nu}$ decay agree with those of previous high-statistics experiments [10,11,13,14]. We note that the most recent result of Wise et al. [13] includes, to some extent, the effect of q^2 -dependence of the form factors f_1 and g_1 . We also note that Lindquist et al. [11] were led to introduce a non-zero contribution from g_2 to the matrix element in order to interpret their results. We wish to stress that, although we could not directly measure the asymmetries α_p , α_e , α_ν in the Λ c.m.s., the results obtained for the fits of these distributions

were completely consistent with the assumptions used for our analysis (in particular $g_2 = 0$) and with our measured value of g_1/f_1 .

6.2 Conclusions

Using the measurement of g_1/f_1 for $\Lambda \rightarrow p\bar{e}\bar{\nu}$ and $\Xi \rightarrow \Lambda e\bar{\nu}$ and the value of $(F + D)$ deduced from the neutron lifetime suggested by Wilkinson [17], $F + D = 1.239 \pm 0.009$, we obtained

$$D/(F + D) = 0.654 \pm 0.043 \quad \text{from } \Lambda \rightarrow p\bar{e}\bar{\nu} ,$$

$$D/(F + D) = 0.600 \pm 0.030 \quad \text{from } \Xi \rightarrow \Lambda e\bar{\nu} .$$

We also computed the value of g_1/f_1 as obtained from the branching ratio measurements for $\Lambda \rightarrow p\bar{e}\bar{\nu}$, $\Xi \rightarrow \Lambda e\bar{\nu}$, and $\Xi \rightarrow \Sigma^0 e\bar{\nu}$. We assumed a value, $\sin \theta_C = 0.231$ [18] for the Cabibbo angle, and corrected for q^2 -dependence of the form factors f_1 and g_1 using the recipe of I. The corrections to the computed values for g_1/f_1 were -3.0%, -10.2%, and -1.2% for $\Lambda \rightarrow p\bar{e}\bar{\nu}$, $\Xi \rightarrow \Lambda e\bar{\nu}$, and $\Xi \rightarrow \Sigma^0 e\bar{\nu}$, respectively. For a more precise comparison, which includes the effect of radiative corrections on both branching ratio and form factor ratio determinations, see Ref. 18.

The values obtained for $|g_1/f_1|$ from the branching ratio measurements were the following:

$$|g_1/f_1| = 0.71 \pm 0.03 \quad \text{for } \Lambda \rightarrow p\bar{e}\bar{\nu}$$

$$(g_1/f_1 = +0.70 \pm 0.03 \text{ from the form factor analysis});$$

$$|g_1/f_1| = 0.30 \begin{smallmatrix} + 0.03 \\ - 0.04 \end{smallmatrix} \quad \text{for } \Xi \rightarrow \Lambda e\bar{\nu}$$

$$(g_1/f_1 = +0.25 \pm 0.05 \text{ from the form factor analysis});$$

$$|g_1/f_1| = 1.25 \begin{smallmatrix} + 0.14 \\ - 0.16 \end{smallmatrix} \quad \text{for } \Xi \rightarrow \Sigma^0 e\bar{\nu}.$$

The branching ratio measurements are thus consistent with the form factor analysis for both $\Lambda \rightarrow p\bar{e}\bar{\nu}$ and $\Xi \rightarrow \Lambda e\bar{\nu}$ decays. We also note that the value $|g_1/f_1| = F + D = 1.25 \begin{smallmatrix} + 0.17 \\ - 0.19 \end{smallmatrix}$ obtained for $\Xi \rightarrow \Sigma^0 e\bar{\nu}$ is in agreement with the value obtained for $(F + D)$ from $n \rightarrow p\bar{e}\bar{\nu}$ decay [17].

We conclude that our results are consistent within the framework of the simple Cabibbo theory used in our analysis. The sensitivity to additional parameters, such as second-class currents or $SU(3)$ symmetry-breaking, is weak, and we see no deviation from the simple theory. The combination of all our results for the various decays, in an over-all fit to the theory, will provide a much stronger test of the assumptions used in our analysis.

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Table 1

$\Xi \rightarrow \Sigma^0 e \bar{\nu}$ events

	Number of reconstructed $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ events (background subtracted)	Signal-to-background ratio	Reconstruction efficiency	Number of $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ events corrected for γ -ray efficiency
Sample 1	198 ± 28	1/2	0.62	319 ± 46
Sample 2	154 ± 19	1/1	0.48	323 ± 40

Table 2

Final samples

Decay mode	Final sample (background included)	$\Xi \rightarrow \Lambda\pi$ background	Residual interaction background	$\Xi \rightarrow \Lambda e\bar{\nu}$ or $\Xi \rightarrow \Sigma^0 e\bar{\nu}$ contamination	Final sample (background subtracted) ^{a)}
$\Lambda \rightarrow p e\bar{\nu}$	7802	546	145	-	$7111 \pm 89 \pm 150$
$\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$	3472	400	61	-	$3011 \pm 62 \pm 65$
$\Xi \rightarrow \Lambda e\bar{\nu}$ Branching ratio sample	1805	< 20	36	< 20	$1769 \pm 42 \pm 53$
$\Xi \rightarrow \Lambda e\bar{\nu}$ Form factor sample	2582	300	40	250	1992 ^{b)}
$\Xi \rightarrow \Sigma^0 e\bar{\nu}$	305	Sum of all backgrounds: 151			$154 \pm 19^c)$

a) The first error is statistical and the second error is the systematic error on the subtraction of the residual backgrounds.

b) In this sample the $\Xi \rightarrow \Lambda\pi$ and $\Xi \rightarrow \Sigma^0 e\bar{\nu}$ contaminations were either simulated or suppressed by further cuts. The maximum number of $\Xi \rightarrow \Lambda e\bar{\nu}$ events used in the form factor analysis was thus about 2000.

c) Statistical error only.

Table 3

Results of $\Lambda \rightarrow p e \bar{\nu}$ form factor analysis

	Sample A: 7802 events		Sample B: 5964 events	
	Result for $ g_1/f_1 $	$\chi^2/\text{d.o.f.}$	Result for $ g_1/f_1 $	$\chi^2/\text{d.o.f.}$
Dalitz plot	0.77 ± 0.04	246/216	0.79 ± 0.04	234/216
T_p	0.78 ± 0.04	11/12	0.75 ± 0.04	11/12
$\cos \theta_{e\bar{\nu}}$	0.74 ± 0.04	15/16	0.74 ± 0.04	16/16

Table 4

Results of $\Xi \rightarrow \Lambda e \bar{\nu}$ form factor analysis

	Sample A: 2582 events		Sample B: 2068 events		Sample C: 1395 events	
	Result for $ g_1/f_1 $	$\chi^2/\text{d.o.f.}$	Result for $ g_1/f_1 $	$\chi^2/\text{d.o.f.}$	Result for $ g_1/f_1 $	$\chi^2/\text{d.o.f.}$
Dalitz plot	0.30 ± 0.06	206/191	0.31 ± 0.06	239/214	0.26 ± 0.06	180/152
T_Λ	0.34 ± 0.07	13/12	0.34 ± 0.07	12/12	0.30 ± 0.07	14/12
$\cos \theta_{e\bar{\nu}}$	0.29 ± 0.06	16/18	0.39 ± 0.08	17/18	0.28 ± 0.07	20/18
Angular distribution α	0.28 ± 0.06	9/18	0.26 ± 0.06	11/18	0.27 ± 0.07	14/18

Table 5

Measurement of f_2 and $\text{Im}(f_1 g_1^*)$

Decay mode	Measured value of f_2	Value predicted for f_2 by CVC	Measured value of $\text{Im}(f_1 g_1^*)$
$\Lambda \rightarrow p e \bar{\nu}$	1.32 ± 0.81	0.974	0.098 ± 0.148
$\Xi \rightarrow \Lambda e \bar{\nu}$	-0.24 ± 0.25	-0.065	0.009 ± 0.076

Table 6

Comparison with previous experiments

Decay mode	Branching ratio measurement		Determination of g_1/f_1	
	This experiment	Previous experiments	This experiment	Previous experiments
$\Lambda \rightarrow p e \bar{\nu}$	$(8.57 \pm 0.36) \times 10^{-4}$ 7111 events	$(8.43 \pm 0.17) \times 10^{-4}$ 10039 events [13] $(8.40 \pm 0.40) \times 10^{-4}$ 1078 events [14]	$+0.75 \pm 0.04$ 7111 events	$+0.734 \pm 0.031$ 10039 events [13] $+0.63 \pm 0.06$ 1078 events [10] $+0.53 \pm 0.09$ 544 events [11]
$\Xi \rightarrow \Lambda(\Sigma^0) e \bar{\nu}$	$(6.5 \pm 0.31) \times 10^{-4}$ 3011 events	$(6.8 \pm 2.2) \times 10^{-4}$ 17 events [15]	-	-
$\Xi \rightarrow \Lambda e \bar{\nu}$	$(5.64 \pm 0.31) \times 10^{-4}$ 2608 events ^{a)}	$(3.0 \pm 1.4) \times 10^{-4}$ 11 events [16]	$+0.28 \pm 0.06$ 1992 events	-
$\Xi \rightarrow \Sigma^0 e \bar{\nu}$	$(0.87 \pm 0.17) \times 10^{-4}$ 154 events	$< 1.4 \times 10^{-4}$ No event seen [16]	-	-

a) As discussed in subsection 4.2.4, the $\Xi \rightarrow \Lambda e \bar{\nu}$ branching ratio was obtained by subtracting the $\Xi \rightarrow \Sigma^0 e \bar{\nu}$ branching ratio from the summed $\Xi \rightarrow \Lambda(\Sigma^0) e \bar{\nu}$ branching ratio.

Figure captions

- Fig. 1 : Plan view of the apparatus. He: helium bags; Li: lithium radiators; Xe: xenon proportional chambers; DC: drift chambers.
- Fig. 2 : Projected angular resolutions ($\Delta\theta_x, \Delta\theta_y$) and ratio of reconstructed π^0 energy to predicted π^0 energy ($E_{2\gamma}/E_{\pi^0}$) for π^0 from $\Sigma^+ \rightarrow p\pi^0$ decays.
- Fig. 3 : Number of spurious γ -rays reconstructed in the case of $\Lambda \rightarrow p\bar{\nu}$ events, for loose lead-glass cuts (Fig. 3a) and tight lead-glass cuts (Fig. 3b) (see Section 2.4).
- Fig. 4 : Distribution of the square of the missing neutrino mass $m_{\bar{\nu}}^2$, for $\Lambda \rightarrow p\bar{\nu}$ and $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}$ decays. Shown are events which passed the final cuts (histogram), events which were rejected by the final cuts (dashed histogram), and Monte Carlo events (curve).
- Fig. 5 : $\Xi \rightarrow \Lambda\pi(\Lambda \rightarrow p\pi)$ interpretation of $\Xi \rightarrow \Lambda\pi(\Lambda \rightarrow p\bar{\nu})$ (Fig. 5a), and $\Xi \rightarrow \Lambda(\Sigma^0)e\bar{\nu}(\Lambda \rightarrow p\pi)$ (Fig. 5b) events. For 33% (resp. 37%) of the data (resp. Monte Carlo) events, no track combination satisfied the $\Xi \rightarrow \Lambda\pi(\Lambda \rightarrow p\pi)$ hypothesis. The residual $\Xi \rightarrow \Lambda\pi(\Lambda \rightarrow p\pi)$ events were well simulated by $\Xi \rightarrow \Lambda\pi$ data, which just failed the final electron cuts (the normalization was done using the total data sample).
- Fig. 6a : Distribution of the effective ($\Lambda\gamma$) mass for $\Xi \rightarrow \Sigma^0 e\bar{\nu}$ candidates (histogram), and for $\Xi \rightarrow \Lambda\pi(\Lambda \rightarrow p\bar{\nu})$ events where a spurious γ -ray was reconstructed (crosses).
- Fig. 6b : Distribution of the effective ($\Lambda\gamma$) mass for $\Xi \rightarrow \Sigma^0 e\bar{\nu}$ events after background subtraction, and for a Monte Carlo simulation including γ -ray reconstruction.
- Fig. 7 : Sensitivity of the angular distribution α to g_1/f_1 for $\Lambda \rightarrow p\bar{\nu}$. Monte Carlo events, weighted with the input value $(g_1/f_1)_I = 0.71$, were fitted by other Monte Carlo events as a function of g_1/f_1 , and the χ^2 -distribution of the fit is shown.

- Fig. 8 : χ^2 -distributions for the fit of the Dalitz plot, T_p , and $\cos \theta_{e\bar{\nu}}$ distributions for $\Lambda \rightarrow p e \bar{\nu}$ (samples A and B).
- Fig. 9 : Projected distributions of the Dalitz plot (T_p and T_e) and of $\cos \theta_{e\bar{\nu}}$ for $\Lambda \rightarrow p e \bar{\nu}$ data (histogram) compared to Monte Carlo (curve).
- Fig. 10 : Angular distributions α , β , n of the E^- in the Λ c.m.s. for $\Lambda \rightarrow p e \bar{\nu}$ data (histogram) compared to Monte Carlo (curve).
- Fig. 11 : Determination of the sign of g_1/f_1 for $\Lambda \rightarrow p e \bar{\nu}$, using the χ^2 -distributions as a function of g_1/f_1 , for the Dalitz plot, the lepton spectrum T_e , and the angular distribution α .
- Fig. 12 : χ^2 -distribution for the fit of the angular distribution α as a function of g_1/f_1 for $E \rightarrow \Lambda e \bar{\nu}$ (sample C).
- Fig. 13 : Projected distributions of the Dalitz plot (T_Λ and T_e) and of $\cos \theta_{e\bar{\nu}}$ for $E \rightarrow \Lambda e \bar{\nu}$ data (histogram) compared to Monte Carlo (curve).
- Fig. 14 : Angular distributions α , β , n of the proton in the Λ c.m.s. for $E \rightarrow \Lambda e \bar{\nu}$ data (histogram) compared to Monte Carlo (curve).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

$\Lambda \rightarrow p e^+ e^-$ Sample B

Fig. 9

Fig. 10

Fig. 11

Fig. 12

$H \rightarrow \Lambda e \bar{\nu}$ Sample B

Fig. 13

$H \rightarrow \Lambda e \bar{\nu}$ Sample B

Fig. 14