First Measurement of the $(\Xi^- \rightarrow \Sigma^- \gamma)/(\Xi^- \rightarrow \Lambda \pi^-)$ Branching Ratio^{*}

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Abstract. In an experiment performed at the CERN SPS charged hyperon beam, we have observed the radiative decay $\Xi^- \rightarrow \Sigma^- \gamma$. From a sample of 11 candidates, containing an estimated background of 1.6 events, the branching ratio is found to be:

$$\Gamma(\Xi^- \rightarrow \Sigma^- \gamma)/(\Xi^- \rightarrow \Lambda \pi^-) = (2.3 \pm 1.0) \times 10^{-4}.$$

1 Introduction

The interest of the radiative decay $\Xi^- \rightarrow \Sigma^- \gamma$ (as well as the decay $\Omega^- \rightarrow \Xi^- \gamma$) has been emphasized by many authors. Within the quark model framework, two-quark transitions (Fig. 1a), where a W boson is exchanged between two quarks of the initial baryon, are believed to play an important role in $\Sigma^+ \rightarrow p \gamma$, $\Lambda \rightarrow n \gamma$ and other radiative decays of hyperons. How-

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Fig. 1 a-d. Diagrams used to calculate the hyperon radiative decay amplitudes: **a** two-quark transition. **b** Penguin diagram (gluon exchange) – the photon can be emitted either from an external quark line or from the internal quark loop. **c** One-quark transition. **d** Pole model with two-particle intermediate state

ever, it is clear that these transitions should be much less important in $\Xi^- \rightarrow \Sigma^- \gamma$ or in $\Omega^- \rightarrow \Xi^- \gamma$, since neither of the initial baryons contains a valence u quark. Contributions to the Ξ^- and Ω^- radiative decay amplitudes can result from “penguin” diagrams (Fig. 1 b) which involve gluon exchange, or from single-quark diagrams (Fig. 1 c). It has been noted that QCD corrections (one gluon loop added to Fig. 1 c) are important for single-quark diagrams. Once they have been taken into account, the contribution of these diagrams is much larger than that of the penguin diagrams for the $\Xi^- \rightarrow \Sigma^- \gamma$ decay [1–4].

The decays $\Xi^- \rightarrow \Sigma^- \gamma$ and $\Omega^- \rightarrow \Xi^- \gamma$ have also been studied theoretically within the framework of the pole model, with two-particle intermediate states (Fig. 1 d), and lower bounds for their branching ratios have been derived from the unitarity principle [5]. The theoretical predictions are summarized in Table 1. It is interesting to notice that in the case of the $\Xi^- \rightarrow \Sigma^- \gamma$ decay, the lower limit from unitarity significantly exceeds the sum of the two contributions calculated from the quark model.

On the experimental side, only upper limits on the $\Xi^- \rightarrow \Sigma^- \gamma$ and $\Omega^- \rightarrow \Xi^- \gamma$ branching ratios have been published so far (see Table 2). The result on the Ξ^- radiative decay mode comes from a bubble chamber experiment at the Brookhaven AGS [6], which observed no candidate in a total sample of 8150 Ξ^- produced by incident K^- at 1.75 GeV/c. The information on the Ω^- radiative decay mode was obtained by two counter experiments in the CERN SPS hyperon beam, with incident Ω^- of 115 GeV/c [7] and 131 GeV/c [8]. Upper limits were derived from the observed distributions of the $(\Omega^- - \Xi^-)$ missing mass combined with information on photon energy and impact position, in events with an identified $\Omega^- \rightarrow \Xi^- + X$ decay.

Table 1. Theoretical predictions for the branching ratios of radiative decays of Ξ^- and Ω^- hyperons

Models	Ref.	$\Xi^- \rightarrow \Sigma^- \gamma$	$\Omega^- \rightarrow \Xi^- \gamma$
Penguin	[2]	$10^{-8} - 10^{-7}$	$10^{-5} - 10^{-4}$
Single quark	[4]	1.8×10^{-5}	6.8×10^{-5}
Pole Model	[5]	1.7×10^{-4}	$1 - 1.5 \times 10^{-5}$
Unitarity	[5]	$> 1.0 \times 10^{-4}$	$> 0.8 \times 10^{-5}$

Table 2. Experimental upper limits on branching ratios (at 90% C.L.)

Authors	Ref.	$\Xi^- \rightarrow \Sigma^- \gamma$	$\Omega^- \rightarrow \Xi^- \gamma$
Yeh et al.	[6]	$< 1.2 \times 10^{-3}$	
Bourquin et al.	[7]		$< 3.1 \times 10^{-3}$
Bourquin et al.	[8]		$< 2.2 \times 10^{-3}$

We have recently reported [9, 10] measurements of the branching ratios of the radiative decays $\Sigma^+ \rightarrow p \gamma$ and $\Lambda \rightarrow n \gamma$ in two experiments carried out at the CERN SPS hyperon beam. In the second of these experiments, the Λ were produced by the decay of incident Ξ^- hyperons, and the final state of interest consisted of a neutron, a photon and a π^- meson. The process ($\Xi^- \rightarrow \Sigma^- \gamma$, $\Sigma^- \rightarrow n \pi^-$) is characterised by precisely the same initial (Ξ^-) and final (n, γ, π^-) particles and, if it exists, can therefore be found in the data gathered for the $\Lambda \rightarrow n \gamma$ experiment. We have indeed observed this process and we report, in the present article, the first measurement of the corresponding branching ratio ($\Xi^- \rightarrow \Sigma^- \gamma$)/($\Xi^- \rightarrow \Lambda \pi^-$).

2 The Experiment

The experimental set up is shown in Fig. 2 (for a detailed description of the apparatus, see [9, 10]). The incident beam particles had a mean momentum of 116 GeV/c. The Ξ^- hyperons were identified by a differential Cherenkov counter (DISC); their trajectories were measured in two clusters of multi-wire proportional chambers (labelled *A* in Fig. 2). Trajectories and momenta of charged decay particles were measured in a magnetic spectrometer consisting of a magnet (SM1), and clusters of MWPCs (*B, C, D, F*) and drift chambers (DC). The scintillator hodoscopes H2 and H3 were used in the trigger logic.

Photons emitted at large angles were detected by a lead glass array (LG) consisting of a lead converter (2.7 radiation lengths), a MWPC, a scintillator hodoscope and a lead glass wall (21.2 r.l.). The MWPC measured the impact point of photons which converted in the lead plate. The pulse height measured in the scintillator hodoscope was used to correct for shower energy deposited in the lead converter and also to improve the discrimination between photon and hadron showers.

Neutrons and photons emitted at small angles were detected by a liquid argon detector (LAD) at the downstream end of the apparatus. The discrimination between photons and neutrons was made possible by the internal structure of the detector: it was divided in three parts along the beam direction, the first two made of 40 and 80 lead plates respectively (4.5 and 9.0 radiation lengths), and the third one of 104 copper plates (2.18 absorption lengths). The charges produced by ionisation were picked up by collector strips oriented alternately in the vertical and horizontal directions.

The purpose of the last magnet (SM2) was to deflect beam particles to an insensitive region in the LAD, to reduce accidental background. Helium bags

Fig. 2. Schematic layout of the apparatus: A, B, C, D, E, F: clusters of MWPCs; DC: clusters of drift chambers; M: multiplicity counter; SM1 and SM2: magnets; H2-H3: scintillator hodoscopes; LG: lead glass array; LAD: liquid argon detector; Ch: threshold Cherenkov counter, Ξ^- : incident hyperon beam; DISC: differential Cherenkov counter. V_1 , T_1 , T_2 : scintillation counters. Coordinates are measured in a frame where X is horizontal, Y vertical and Z along the nominal beam axis with the origin at the centre of the last quadrupole magnet of the beam

were installed in front of the LAD, between the last two E chamber clusters, and inside the two magnets, to reduce photon conversion probability. The multiplicity counter (M) and the threshold Cherenkov counter (Ch) were not used in the present experiment.

The trigger demanded an incident Ξ^- (defined by beam scintillators and the DISC) and only one charged decay particle (defined by a single hit cell in H2). Up to two cells were allowed to fire in H3 to allow for possible back-leakage of showers in the LG array. These trigger conditions accepted the radiative decays $\Xi^- \rightarrow \Sigma^- \gamma$ and $\Xi^- \rightarrow \Lambda \pi^-$, $\Lambda \rightarrow n \gamma$ (excepted those in which a photon converted upstream of H2), but also the far more abundant decays $\Xi^- \rightarrow \Lambda \pi^-$, $\Lambda \rightarrow n \pi^0$. A very small proportion of the Σ^- hyperons in the beam triggered the DISC accidentally; they constituted about 1% of our triggers. The trigger conditions rejected the $\Xi^- \rightarrow \Lambda \pi^-$, $\Lambda \rightarrow p \pi^-$ decays if the Λ decay occurred upstream of H3.

For a total intensity of 1.6×10^6 particles per SPS burst, 200 Ξ^- were tagged by the DISC. A total of 1.44×10^6 events which satisfied the trigger requirements were recorded on tape during 10 days of running.

3 Geometrical Reconstruction and Initial Event Selection

In order to have enough lever arm to measure the incident Ξ^- and the outgoing π^- , we looked for events where both the Ξ^- and the Σ^- decayed between the last cluster of beam chambers and the second cluster of drift chambers. For this category of events, a Monte Carlo simulation shows that the photon strikes the LAD in about 60% of the cases and the LG in 25% of the cases, whereas the neutron always hits the LAD. The geometrical reconstruction of the events was done in two main steps: reconstruction of the tracks of the charged particles in the spectrometer and reconstruction of showers in the calorimeters. In each step, a first selection of events was carried out based on the topology of the reconstructed tracks and showers.

The incident particle track was reconstructed in the beam telescope. We required a single beam track, with measured angles within ± 0.25 mrad of the mean beam direction in both horizontal and vertical projections in order to reject triggers associated with Ξ^- decays occurring upstream of the last beam chamber.

The momentum of the incident particle was determined to within $\pm 2\%$ from its direction in the horizontal plane, using the characteristics of the beam optics.

The secondary track was reconstructed in the drift chambers upstream and downstream of SM1. The two segments were then associated, allowing a measurement of the particle momentum with a typical precision of $\pm 2\%$. We required a single negatively charged particle in the spectrometer, with measured trajectory and momentum. The track reconstruction procedures are described in [9] and [10]. At our beam energy, the maximum angle between the Ξ^- and Σ^- trajectories is 1.1 mrad, and our angular resolution was in most cases insufficient to establish the presence of a kink on the primary track. We therefore made no attempt to reconstruct the intermediate (Σ^-) track.

In order to reject events in which the Ξ^- or the Σ^- decayed downstream of SM1, we required the measured momentum of the secondary particle to be smaller than 50 GeV/c, (the momentum of the π^- from Ξ^- or Σ^- decay cannot exceed 39 GeV/c) and the angle between the incident and the secondary particle tracks to be larger than 1 mrad.

The coordinates of the point of closest approach between the incident and secondary tracks were computed and a loose cut applied on the distance of approach (10 mm) to reject accidental associations. This point of closest approach is obviously not the vertex ($\Sigma^- - \pi^-$) but is close to it, since in most cases the ($\Sigma^- - \pi^-$) angle is between 10 and 16 mrad, thus much larger than the ($\Xi^- - \Sigma^-$) angle. The z coordinate of this point was required to lie in the range from 3.70 to 7.50 m ("decay region" in Fig. 2). At this stage, 32% of the initial sample of events remained.

The shower reconstruction methods and, in particular, the procedures to identify photon and hadron showers, are extensively described in [9] and [10]. The calibration, resolutions and efficiencies of the LAD, given in [9] and [10], are also valid for this experiment, since the photon energy ranges are similar. The spatial resolution (σ) was found to be 4 mm for photon showers and 8 mm for neutron showers. The energy resolution for photons was well represented by the formula $\sigma(E)/E = 20\%/\sqrt{E}$ (E in GeV). The neutron energy could not be measured, since on average only 60% (with large fluctuations) of this energy was deposited in the LAD. The efficiency for neutron detection was $(88 \pm 4)\%$. The reconstruction efficiency for photon showers varied with energy, rising from about 50% at 2 GeV to close to 100% above 6 GeV. This efficiency was significantly degraded when the neutron and photon showers over-

lapped, in particular when their distance in projection was less than 50 mm. For the LG, the resolutions of the photon energy and position were $\sigma(E)/E = 25\%/\sqrt{E}$ (E in GeV) and $\sigma(x) = \sigma(y) = 5$ mm in the energy range of 2 to 10 GeV.

We first selected the events having a single hadron shower in the LAD (the π^- were always deflected away from the LAD). We required this shower not to be associated with a charged particle track, in order to suppress events due to $\Xi^- \rightarrow \Lambda \pi^-$, $\Lambda \rightarrow p \pi^-$ in which the Λ decayed downstream of H3. We then required a photon shower, which may have been either in the LAD or in the LG. Events with an additional photon shower in either detector were rejected to suppress $\Xi^- \rightarrow \Lambda \pi^-$, $\Lambda \rightarrow n \pi^0$, $\pi^0 \rightarrow \gamma \gamma$ decays. At this stage, we were left with 80092 events which represented 5.6% of the initial sample. For 65537 events, the photon was observed in the LAD, for 14555 events it was detected in the LG. From this point of the analysis, these two subsamples were treated separately, because of the different performance characteristics of the two detectors.

For the events with a photon in the LAD, the problems of pattern recognition were identical to those met in our previous analysis [10]. Therefore we applied the same criteria to reject events which might have presented reconstruction problems. Thus, we required the photon energy to be larger than 4 GeV (55345 events left), the distance in both projections (x , y) between the neutron and photon showers to be larger than 60 mm (39286 events) and the difference between the photon energies measured in the x and y projections to be smaller than 2 GeV (32701 events).

The energy spectrum of the showers reconstructed in the lead glass was strongly peaked below 2 GeV. This may be due to genuine low energy photons (from π^0 decay or bremsstrahlung) or to random counts. On the other hand, the energy spectrum of the photons from the decay $\Xi^- \rightarrow \Sigma^- \gamma$ does not extend significantly below 2 GeV. Therefore we required the photon energy to be larger than 2 GeV (5851 events left). To suppress possible hadronic showers, we further demanded signals with a minimum pulse height in the corresponding scintillator and in the associated region of the proportional chamber (3350 events left). In these conditions, the detection efficiency for photons was estimated to be $(82 \pm 5)\%$. A cut was also applied at 25 mm on the distance between the shower centre and the edges of the lead glass array, to avoid problems of energy leakage. This reduced the LG sample to 2873 events.

A detailed Monte-Carlo simulation of the experiment was necessary in order to assess the efficiency of the apparatus and determine its acceptance. The

resolutions and efficiency functions mentioned above were parametrized and introduced into the M.C. program. This program already used in our previous analyses [9, 10] is extensively discussed in these references.

4 Selection of $\Xi^- \rightarrow \Sigma^- \gamma$ Candidates and Evaluation of the Background

For both subsamples of events, we computed the missing mass between the incident Ξ^- and the outgoing π^- . The resulting mass spectra are shown in Figs. 3a, b. These spectra show a peak centred at the Λ mass. This demonstrated that most of our events were in fact $\Xi^- \rightarrow \Lambda \pi^-$, $\Lambda \rightarrow n \pi^0$ decays in which one photon escaped detection, either because of the incomplete solid angle coverage or because of

inefficiencies. The width of the peak (7 MeV/c² FWHM) is consistent with the resolution expected at the Λ mass.

The next step of the analysis made use of the kinematics of the decays $\Xi^- \rightarrow \Sigma^- \gamma$, $\Sigma^- \rightarrow n \pi^-$. Using the following measured quantities:

- the momentum and direction of the Ξ^- ,
- the coordinates of the impact point of the photon and its energy,
- the momentum and direction of the π^- ,
- the coordinates of the impact point of the neutron, and under the assumption of a $\Xi^- \rightarrow \Sigma^- \gamma$ decay, we calculated the angle between the Ξ^- and photon trajectories, and the coordinates of the Ξ^- decay point. The momentum and direction of the Σ^- were computed using four-momentum conservation. The Σ^- decay vertex was then defined by the point of closest approach between the Σ^- and π^- trajectories. These calculated decay points were restricted to the decay region defined above (within the errors), which reduced the LAD sample to 6455 events and the LG sample to 1894 events.

By setting the $(n-\pi^-)$ effective mass to the Σ^- mass, we calculated the neutron energy and deduced the global energy balance ΔE . In Figs. 4a, b, we show the observed distributions of the quantity ΔE . Qualitatively, genuine $\Xi^- \rightarrow \Sigma^- \gamma$ decays are expected to peak around $\Delta E=0$. Indeed, the spectrum of ΔE for the LAD events (Fig. 4a) shows a cluster of about 30 events centred at 0. Most of the events fall at the sides of the plot, outside the interval between -20 GeV and $+20$ GeV. This feature is well reproduced by the M.C. simulation of the decays $\Xi^- \rightarrow \Lambda \pi^-$, $\Lambda \rightarrow n \pi^0$. The ΔE spectrum for the LG events (Fig. 4b) shows the same shape, with less statistics (about 10 events around $\Delta E=0$).

The M.C. simulation of genuine ($\Xi^- \rightarrow \Sigma^- \gamma$, $\Sigma^- \rightarrow n \pi^-$) events predicted a peak with a width (σ) of 4 GeV centred at 0 GeV, plus tails extending up to 20 GeV. A cut on ΔE at ± 8 GeV, which defines the “central region” of the ΔE plot, was predicted to retain 80% of the good events while rejecting all the background due to the $\Xi^- \rightarrow \Lambda \pi^-$, $\Lambda \rightarrow n \pi^0$ decays. It was important, however, to check whether badly reconstructed events of the type $\Xi^- \rightarrow \Lambda \pi^-$, $\Lambda \rightarrow n \pi^0$ could simulate the ($\Xi^- \rightarrow \Sigma^- \gamma$, $\Sigma^- \rightarrow n \pi^-$) kinematics, thereby populating the central region of the ΔE plots.

For this purpose, we selected a sample of events with two photon showers, which consisted almost entirely of $\Lambda \rightarrow n \pi^0$ events. This sample was subjected to the selection procedure described above, each event being treated as two single-photon combinations by ignoring alternately one of the photon showers. The resulting ΔE spectra are shown in Fig. 5a (4089 combinations with one photon in the LAD) and Fig. 5b

Fig. 3 a, b. Distribution of the $(\Xi^- - \pi^-)$ missing mass: **a** Data sample with the photon detected in the LAD. **b** Data sample with the photon detected in the LG

a

b

Fig. 4 a, b. Distribution of the global energy balance: $\Delta E = E_{\Sigma^-} - (E_{\gamma} + E_{\pi} + E_{\pi^0})$ **a** Data sample with the photon detected in the LAD. **b** Data sample with the photon detected in the LG. The dashed area shows the distribution for the events which have $\Delta P_T < 60$ MeV/c. The inset shows the distribution of ΔE in the range of -10 GeV to 10 GeV

(1794 combinations with one photon in the LG). It can be seen from Fig. 5a that the $\Lambda \rightarrow n\pi^0$ events reproduce the main features of the background in Fig. 4a, namely a plateau at each side of the distribution and a deep central valley. In the range of ΔE between -8 and $+8$ GeV, there are a few events, which are fairly uniformly distributed (see inset of Fig. 5a). Taking into account the different sample sizes, this indicates the presence of about 12 badly reconstructed $\Sigma^- \rightarrow \Lambda\pi^-$, $\Lambda \rightarrow n\pi^0$ events in the central region of the ΔE plot of Fig. 4a. Comparing Figs. 4b and 5b, one is led to expect about 5 badly reconstructed $\Lambda \rightarrow n\pi^0$ events in the same ΔE range, among the 10 events of the LG sample.

a

b

Fig. 5a, b. Distribution of the global energy balance: $\Delta E = E_{\Sigma^-} - (E_{\gamma} + E_{\pi} + E_{\pi^0})$, for two-photon events treated as one-photon events. **a** Data sample with a photon in the LAD. **b** Data sample with a photon in the LG. The dashed area shows the distribution for the events which have $\Delta P_T < 60$ MeV/c. The inset shows the distribution of ΔE in the range of -10 GeV to 10 GeV

As we have seen before, about 1% of our triggers are in fact due to incident Σ^- hyperons. A proportion of these Σ^- are accompanied by an accidental photon. To investigate whether this could be a source of background, we computed the missing mass between the beam particle, assigned the Σ^- mass, and the outgoing pion. Figure 6 shows the distribution of this missing mass for the LAD events in the central region of ΔE . The peak at the neutron mass indicates a background of 5 to 8 events due to the incident Σ^- . For the LG sample, no incident Σ^- remained at this stage; they have been all rejected by the severe selection criteria applied to the photon showers.

The global transverse momentum balance ΔP_T ,

Fig. 6. Distribution of the $(\Sigma^- - \pi^-)$ missing mass: data sample with a photon in the LAD and $|AE|$ (defined in Sect. 4) less than 8 GeV. The dashed area shows the distribution for the events which have $\Delta P_T < 60$ MeV/c

computed under the assumption of a $(\Xi^- \rightarrow \Sigma^- \gamma, \Sigma^- \rightarrow n\pi^-)$ decay, has been used to suppress further the background due to $\Lambda \rightarrow n\pi^0$ decays and to incident Σ^- . We have applied a cut on ΔP_T at 60 MeV/c, (99% acceptance for good events, according to the M.C. simulation) whose effect on ΔE distributions is shown by the dashed area of Fig. 4 and 5. In the central region of the ΔE plot (-8 GeV to $+8$ GeV), this cut selected 11 events with the photon in the LAD and two events with the photon in the LG. The distribution of the $(\Sigma^- - \pi^-)$ missing mass for the selected events is also shown by a dashed area in Fig. 6. The peak at the neutron mass has disappeared. All the events with a missing mass above 0.97 GeV/c² have also disappeared. From the M.C. simulation, we expect no good events in this region.

Applying the ΔP_T cut on the two-photon events treated as one-photon combinations, only two events remain. With these two events, one can make a first estimate of the background due to badly reconstructed $\Xi^- \rightarrow \Lambda\pi^-$, $\Lambda \rightarrow n\pi^0$ in our candidates. Assuming that the proportion of events contributing to the background is the same for the $(\Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow n\pi^0)$ sample with one detected photon as for the simulated sample with both photons detected but one ignored, we were led to an estimate of 3.2 background events among the LAD candidates. The same type of analysis led to an estimate of zero background events in the LG candidates.

An independent estimate of the $(\Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow n\pi^0)$ background was based on visual scanning of the displays of the calorimeter information. A scan of the 11 LAD candidates revealed that two events

contained a second small signal which had been missed by the pattern recognition program. Interpreting this signal as a photon and combining it with the first photon yielded an effective mass compatible with the π^0 mass in both cases. In a scan of single-photon events with large $|AE|$, a second small photon signal was found in one half of the events. Thus the scanning method led to a reduced sample of 9 candidates, containing an estimated background of 2 ($\Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow n\pi^0$) decays. For the LG sample, the visual scanning revealed no spurious event.

We have also examined computer displays of the track information, to see if any accidental track, interaction or π^- decay led us to misinterpret an event as a $(\Xi^- \rightarrow \Sigma^- \gamma, \Sigma^- \rightarrow n\pi^-)$ decay. No event of this type was found. We also verified by a M.C. simulation that $\pi^- \rightarrow \mu^- \bar{\nu}$ decays in $\Xi^- \rightarrow \Lambda\pi^-$ events were not an appreciable source of background.

Finally, subtracting the background identified by scanning (11 candidates – 2 identified background events) and taking the average of the two above estimates of the residual background (1.2 and 2), we were left with a signal of 7.4 events in the LAD sample and 2 events in the LG sample (two candidates and zero background events).

5 Results and Discussion

The branching ratio $BR = \Gamma(\Xi^- \rightarrow \Sigma^- \gamma) / \Gamma(\Xi^- \rightarrow \Lambda\pi^-)$ was computed as follows:

$$BR = \frac{N(\Xi^- \rightarrow \Sigma^- \gamma)}{N(\Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow n\pi^0)} \times \frac{A(\Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow n\pi^0)}{A(\Xi^- \rightarrow \Sigma^- \gamma)} \times \frac{\Gamma(\Lambda \rightarrow n\pi^0)}{\Gamma(\Lambda \rightarrow \text{all})}$$

where

$N(\Xi^- \rightarrow \Sigma^- \gamma)$ is the number of events attributed to the $\Xi^- \rightarrow \Sigma^- \gamma$ decay mode (7.4 for the LAD sample and 2 for the LG sample);

$A(\Xi^- \rightarrow \Sigma^- \gamma)$ is the acceptance calculated by the M.C. program (0.087 for the LAD sample, 0.042 for the LG sample). These numbers include the geometrical acceptance and the efficiency of the apparatus;

$N(\Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow n\pi^0)$ is the number of events attributed to this decay, with one photon detected in the LAD (13 509 events);

$A(\Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow n\pi^0)$ is the corresponding acceptance (0.106).

The branching ratio $\Gamma(\Lambda \rightarrow n\pi^0) / \Gamma(\Lambda \rightarrow \text{all})$ is taken from [11] (0.358 ± 0.005).

For the normalisation, we relied on the number of $(\Xi^- \rightarrow \Lambda\pi^-, \Lambda \rightarrow n\pi^0)$ events with one photon observed in the LAD, because they had the same topolo-

gy as the LAD candidates and therefore the same reconstruction efficiencies. The number of 13509 events comes from our analysis of the $\Lambda \rightarrow n\gamma$ decay [10].

For the evaluation of the branching ratio from the LG sample, we used the same normalisation and not the ($\Xi^- \rightarrow \Lambda\pi^-$, $\Lambda \rightarrow n\pi^0$) events where the only photon seen is in the LG, because the acceptance for this latter type of events is small and poorly determined. The quoted acceptance took into account the relative efficiencies of the two detectors.

Two measurements of the $\text{BR}(\Xi^- \rightarrow \Sigma^- \gamma / \Xi^- \rightarrow \Lambda\pi^-)$ were obtained:

$$(2.39_{-0.83}^{+1.27}) \times 10^{-4} \text{ for the LAD sample, and}$$

$$(1.33_{-0.86}^{+1.74}) \times 10^{-4} \text{ for the LG sample;}$$

the quoted errors are only statistical. (These errors are given by the 68% confidence interval, using the conventional Clopper-Pearson limits [12]).

Among the systematic errors, let us consider first those which affect independently the two results. The uncertainty on the photon energy calibration results in a systematic error of at most 10% on the number of candidates in the LAD sample; the corresponding value is about 25% for the LG sample. The acceptances (including the efficiency of the apparatus) for good events are known to within 4% (LAD) and 7% (LG). Changing, within reasonable limits, the values of the cuts in the kinematical selection procedure leads to variations of BR up to 20% for the LAD sample (20% for the LG sample); these figures were taken as the value of the systematic errors from this contribution. A systematic error of $\pm \frac{10}{20}\%$ on the numbers of LAD candidates comes from the uncertainty on the estimated background.

The various contributions to the systematic errors mentioned above were added quadratically to the statistical error for each estimate of BR. The weighted

average of the branching ratio was then computed:

$$\text{BR} = (2.27 \pm 0.99) \times 10^{-4}.$$

To the error quoted, one still has to add the contribution of systematic errors which are common to the two estimates of BR. The error on the value of the acceptance for good events due to the uncertainties in the simulation of the incident beam (in particular $\Xi^- \rightarrow \Sigma^- \gamma$ decays in the DISC) is 7%. The error on the acceptance for $\Xi^- \rightarrow \Lambda\pi^-$, $\Lambda \rightarrow n\pi^0$, due essentially to the overlap between neutron and photon showers, is of the order of 7%.

We are therefore led to the final result:

$$\text{BR} = (2.27 \pm 1.02) \times 10^{-4}.$$

This is the first measurement of the $\Xi^- \rightarrow \Sigma^- \gamma$ branching ratio. This result is of particular interest because it provides information on a process which cannot proceed through a two-quark transition. This result is in agreement with the theoretical value based on the pole model (1.7×10^{-4}) and consistent with the lower limit deduced from unitarity within the same model (10^{-4}). On the other hand, it significantly exceeds the contributions calculated from the single-quark transition diagram or from the penguin diagram.

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