First Measurement of the $\Lambda \rightarrow n\gamma$ Branching Ratio^{*}

S.F. Biagi^{6,a}, M. Bourquin³, R.M. Brown⁷, H.J. Burckhart^{4,b}, Ch. Doré⁵, P. Extermann³,
M. Gailloud⁵, C.N.P. Gee⁷, W.M. Gibson¹, R.J. Gray⁷, P. Jacot-Guillarmod⁵, P.W. Jeffreys⁷,
W.C. Louis^{7,c}, Th. Modis^{3,d}, P. Mühlemann^{3,e}, R.C. Owen¹, J. Perrier³, K.J.S. Ragan³,
Ph. Rosselet⁵, B.J. Saunders⁷, P. Schirato^{3,f}, H.W. Siebert⁴, V.J. Smith¹, K.-P. Streit^{2,g},
J.J. Thresher⁷, R. Weill⁵, A.T. Wood¹, C. Yanagisawa^{7,h}.

¹ H.H. Wills Physics Laboratory, University of Bristol, Bristol BS8 1TL, UK

² CERN, CH-1211 Geneva 23, Switzerland

³ University of Geneva, CH-1211 Geneva 4, Switzerland

⁴ Physikalisches Institut, Universität Heidelberg, Federal Republic of Germany

⁵ University of Lausanne, CH-1015 Lausanne, Switzerland

⁶ Queen Mary College, University of London, London E1 4NS UK

⁷ Rutherford Appleton Laboratory, Chilton, Oxon OX11 0QX, UK

Received 18 October 1985

Abstract. In an experiment performed at the CERN-SPS charged hyperon beam, we have observed the radiative decay $\Lambda \rightarrow n\gamma$, using well identified Λ from the decays of Ξ^- of 116 GeV/c momentum. Neutrons and photons from the Λ decays were observed in liquid argon and lead glass detectors. From a sample of 31 candidates, containing an estimated background of 7.3 events, the decay branching ratio was measured to be $\Gamma(\Lambda \rightarrow n\gamma)/\Gamma(\Lambda \rightarrow \text{all}) = (1.02 \pm 0.33) \times 10^{-3}$.

1. Introduction

Using the CERN-SPS charged hyperon beam, we have carried out two experiments on the hyperon

radiative decays, one with incident Σ^+ to study the decay $\Sigma^+ \rightarrow p\gamma$, the other with incident Ξ^- to search for the decays $\Lambda \rightarrow n\gamma$ (the Λ resulting from the decay $\Xi^- \rightarrow \Lambda\pi^-$) and $\Xi^- \rightarrow \Sigma^- \gamma$. These two experiments used essentially the same apparatus, which included a magnetic spectrometer and two neutral particle detectors.

The results concerning the Σ^+ radiative decay have already been published [1]. In the present article, we report the first observation of the decay $\Lambda \rightarrow n\gamma$, and a measurement of the corresponding branching ratio [2].

The plan of this article is the following. The apparatus and the trigger logic are described in Sect. 2 and the event reconstruction and initial selection in Sect. 3. In Sect. 4 we discuss the Monte Carlo simulation of the experiment, the detector efficiencies and the selection of the candidates for the radiative decay $\Lambda \rightarrow n\gamma$. The results are presented and discussed in Sect. 5.

A discussion of the present theoretical and experimental knowledge of hyperon radiative decays is given in [1]. The existing experimental results concern mainly the decay $\Sigma^+ \rightarrow p\gamma$, and most of the theoretical calculations use the decay rate for this process as normalisation. Therefore, experimental data on other radiative decays are urgently needed for a meaningful comparison of theory and experiment.

^{*} Work supported in part by the UK Science and Engineering Research Council, the Swiss National Foundation for Scientific Research and the Bundesministerium für Forschung und Technologie, Federal Republic of Germany

^a Now at University of Liverpool, UK

^b Now at CERN, Geneva, Switzerland

^c Now at Princeton University, NJ, USA

^d Now at Digital Equipment Corporation, Geneva, Switzerland

^e Now at Zellweger-Uster, Hombrechtikon, Switzerland

^f Now at Hôpital cantonal, Geneva, Switzerland

^g Also at Physikalisches Institut, Universität Heidelberg, FRG

^h Now at State University of New York at Stony Brook, NY, USA

2. The Experiment

The aim of the experiment was to detect the radiative decay $\Lambda \rightarrow n\gamma$ among the much more abundant decays $\Lambda \rightarrow n\pi^0$, $\pi^0 \rightarrow \gamma\gamma$. The Λ were produced by the decay of Ξ^- from the charged hyperon beam at the CERN SPS. The momentum and direction of the Λ were determined from the momenta and directions of the Ξ^- and π^- . The neutral particles resulting from the Λ decay were observed in two calorimeters: a liquid argon detector and a lead glass array.

Only a brief description of the hyperon beam and of the apparatus is given here, since they are described in detail in [1]. The trigger logic is fully discussed, as it is specific to this particular experiment.

2.1. The Apparatus

The hyperons were produced by 250 GeV/c protons incident on a BeO target. A magnetic channel selected negatively charged particles within a 10% momentum band, which in this experiment was centred at 116 GeV/c, and the Ξ^- were identified with a DISC Cherenkov counter. Two sets of multiwire proportional chambers (*A* in Fig. 1) allowed the momenta of individual beam particles to be determined from the momentum-angle correlation given by the beam optics.

A magnetic spectrometer was used to measure the momenta of charged decay particles. It consisted of two magnets (SM1 and SM2), sets of MWPC (*B*, *C*, *D*, *E*, *F*) and drift chambers (DC), and of scintillation counter hodoscopes. The efficiency of the MWPC's was larger than 98%; that of the drift chambers was of the order of 95%, except in a circular spot in the region of the beam where it fell

to about 70%. The apparatus upstream of SM2 was used to analyse the kinematics of the Ξ^- decay. In this experiment, the only purpose of the second magnet SM2 was to deflect the beam particles away from the centre of the photon and neutron distributions, in order to reduce accidental background.

Small angle photons were detected by the liquid argon detector (LAD) at the downstream end of the apparatus. The active part of the LAD consisted of a stack of radiator and collector plates immersed in liquid argon. The collectors were divided into strips, alternate planes having the strips aligned along the vertical and horizontal directions. The detector was divided longitudinally into three parts, blocks *A*, *B*, *C* (see Table 4 of [1] for details). This structure was chosen in order to allow the identification of the incident particle, since photon showers deposited most of their energy in blocks *A* and *B* (Pb radiator, 13.5 radiation lengths, 0.93 absorption lengths), whereas hadronic showers developed mainly in block *C* (Cu radiator, 2.18 absorption lengths).

The purpose of the lead glass array (LG) was to detect photons emitted outside the solid angle subtended by the LAD. It consisted of 11 (horizontal) $\times$ 7 (vertical) blocks with the central 3×3 blocks missing. In front of it, were a proportional chamber with a lead converter and a scintillator hodoscope.

The scintillator hodoscopes H2 and H3 consisted of 18 and 32 cells respectively. They accepted π^- passing through the aperture of SM1 from upstream Ξ^- decays.

The multiplicity counter *M* and the Cherenkov counter Ch were not used in this experiment.

2.2. Trigger Logic

An incident beam particle was defined by the coincidence between the beam counters: (BEAM)=(T1),

Fig. 1. 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; *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

(T2), ($\sqrt{V1}$). The annular veto counter V1 allowed the rejection of events in which the beam particle was accompanied by another particle in the beam halo.

An incident Ξ^- was defined by (BEAM) and an eightfold coincidence of the 8 photomultipliers of the DISC.

To reject events where the decay $\Xi^- \rightarrow \Lambda \pi^-$ was followed by $\Lambda \rightarrow p \pi^-$, we required that exactly one cell be hit in H2 ($\Sigma H2=1$). In H3, we accepted from 0 to 2 cells hit ($\Sigma H3 < 3$) allowing for one extra spurious particle (e.g. beam track or LG back-scattering). These conditions rejected most of the events where one photon converted into an $e^+ e^-$ pair. The trigger was therefore defined as:

(EVENT)

$$=(\text{BEAM}) \times (\text{DISC}) \times (\Sigma H2=1) \times (\Sigma H3 < 3).$$

Each 1.5 s SPS burst yielded about 200 identified Ξ^- among a total of 1.6×10^6 particles, mostly pions. About 70 events/burst satisfied the main trigger requirements. A total of 1.44×10^6 events were recorded on magnetic tape.

3. Reconstruction and Initial Event Selection

The geometrical reconstruction of the events was done in two parts: a search for a decay vertex in the upstream region of the spectrometer (corresponding to the decay $\Xi^- \rightarrow \Lambda \pi^-$); and a search in the neutral particle detectors for showers due to neutrons and photons from the decays $\Lambda \rightarrow n \pi^0$ or $\Lambda \rightarrow n \gamma$. A first selection of events was then made on the basis of topological and geometrical criteria. For the surviving events, a kinematical reconstruction of the decay $\Xi^- \rightarrow \Lambda \pi^-$ was attempted.

3.1. Charged Particle Tracks

The track of the incident particle was reconstructed using the coordinates measured in the beam chambers (A). The tracks of secondary particles upstream of SM1 were reconstructed using the coordinates measured in the drift chambers (DC). A kink, indicating the decay of a beam particle, was sought between these tracks. The parameters of the tracks were then recalculated using the information from all the chambers traversed.

Downstream of SM1, tracks were also reconstructed and, whenever possible, matched with upstream tracks in order to measure the momentum of the particles. In a later step, an attempt was made to match tracks downstream of SM1 or of SM2 with showers in the calorimeters. The reconstruction algorithms are described in [1].

The beam optics [3] provided a strong correlation between the momentum P of the incident

particle and its horizontal angle θ_x . This allowed a determination of the incident momentum relative to the mean momentum to within ± 1 GeV/c, from the relation $P(\theta_x) = P_0 + G \theta_x$. The constants P_0 and G were determined by measuring the momenta of beam particles, as calculated from their deflection in the magnets using polynomial functions deduced from the field maps. This gave $P_0 = 116.1 \pm 0.5$ GeV/c and $G = 11.3 \pm 2.5$ GeV/c/mrad, resulting in an overall uncertainty of $\pm 2\%$. The method also provided a cross calibration of the magnets SM1 and SM2. The absolute calibration of the magnetic spectrometer was checked by computing the effective $(p \pi^-)$ and $(p \pi^- \pi^-)$ masses in the decays $\Lambda \rightarrow p \pi^-$ and $\Xi^- \rightarrow \Lambda \pi^-$ respectively, and comparing them with the known masses of the Λ and the Ξ^- . The means of the effective mass distributions were equal to the expected values within 0.3 MeV/c², and the widths were 4 and 7 MeV/c² FWHM, respectively.

3.2. Neutral Particle Showers

The geometry of this experiment was such that for 98% of the $\Lambda \rightarrow n \pi^0$ decays and 91% of the $\Lambda \rightarrow n \gamma$ decays at least one photon hit either the LAD or the LG, and that all neutrons from either decay mode reached the LAD.

The algorithms used for the shower reconstruction in the LAD are described in [2] and [4]. Showers were identified as either neutron-induced or photon-induced on the basis of their longitudinal development. This identification was complicated in some cases by an overlap of the neutron shower and one of the photon showers. This point will be discussed below.

The spatial resolution of the LAD was measured to be ± 3 mm for electron-induced showers, and ± 8 mm for showers produced by charged hadrons. These values are representative of the resolution expected for photon and neutron-induced showers, respectively. A tolerance of 25 mm was used for the association of the observed showers with charged particle trajectories reconstructed in chambers downstream of SM2.

The energy E of a photon giving a shower in the LAD was given by the expression: $E = \alpha S + \beta$, where S is the sum of the signals from the horizontal and vertical strips in the region of the shower. The linearity of this relation was checked in the range 6–22 GeV/c using $\Sigma^+ \rightarrow p \pi^0$ decays [1]. The calibration constants:

$$\alpha = 0.0142 \pm 0.0004 \text{ [GeV/ADC count]},$$

$$\beta = 0.40 \pm 0.16 \text{ GeV}$$

were obtained from the two-photon events with photon energy between 4 and 20 GeV in our $\Xi^- \rightarrow \Lambda \pi^-$, $\Lambda \rightarrow n \pi^0$, $\pi^0 \rightarrow \gamma\gamma$ data. A sample of particularly clean events (3 well separated showers) was selected for this purpose. The constants were adjusted to make the $\gamma\gamma$ and $n\gamma\gamma$ effective masses coincide with the known π^0 and Λ masses. The quoted errors include the spread from run to run, and the systematic uncertainties of the method. The values of α and β differ from the ones quoted in [1] because of different settings of the LAD electronic circuits between the two experiments.

The energy resolution, measured with electrons of energy between 6 and 24 GeV, is well represented by the formula $\sigma(E)/E \approx 20\%/\sqrt{E}$ (E in GeV).

For hadronic showers, about 60% (with large fluctuations) of the incident energy was deposited in the LAD. Therefore the signal S is not a useful measure of the hadron energy.

The shower reconstruction in the LG, as well as the method of calibration, are described in [1]. The spatial resolution of the LG has been measured to be ± 5 mm for photon showers starting in the lead converter and observed in the associated chamber. For hadronic showers, the spatial resolution is determined by the lateral dimensions of the blocks (150 mm $\times$ 150 mm) and was found to be ± 50 mm. Photon showers were required not to be associated with charged particles seen in the chambers in front of the lead plate. A minimum distance of 100 mm horizontally and vertically was required between charged particle tracks extrapolated to the LG and the centre of the shower. This criterion was used in particular to reject showers induced by the π^- from Ξ^- decay.

3.3. Initial Event Selection

A first event selection was made on the basis of topological criteria. We demanded a single charged track through the length of the apparatus and allowed at most one extra spurious track (not associated with the beam and observed in only one section of the spectrometer). We required also a minimum of 1 and a maximum of 5 showers in the calorimeters. The number of events successfully passing these tests was about 1 million.

Further geometrical criteria were applied to select events containing a $\Xi^- \rightarrow \Lambda \pi^-$ decay in the fiducial region. The reconstructed trajectory of the beam particle was required to lie within a restricted angular region, in order to reject early Ξ^- decays. Events were required to have exactly one reconstructed decay vertex (kink) formed by the beam track and a secondary track passing through the

Fig. 2. Distribution of the π^- laboratory decay angle at the vertex of the Ξ^- decay (histogram). The Monte Carlo distribution for the decay $\Xi^- \rightarrow \Lambda + \pi^-$ (curve) is normalized to the number of events in the interval 1–12.5 mrad. The arrow indicates the position of the cut

Fig. 3. Distribution of the missing mass at the vertex of the $\Xi^- \rightarrow \pi^- + X$ decay (histogram). The Monte Carlo distribution for the decay $\Xi^- \rightarrow \Lambda + \pi^-$ (curve) is normalized to the number of events in the interval 1,105–1,125 MeV/ c^2 . The arrows indicate the position of the cut

spectrometer. The Z coordinate of the kink had to be within the interval 3.70–7.50 m, the closest distance of approach of the two tracks involved had to be less than 2 mm, and the kink angle had to be larger than 1 mrad. (see Fig. 2).

The compatibility of the event with a $\Xi^- \rightarrow \Lambda \pi^-$ decay was then checked by computing the $\Xi^- - \pi^-$ missing mass (Fig. 3), which had to be within ± 10 MeV/ c^2 of the known Λ mass. At this stage 315,500 events, identified as $\Xi^- \rightarrow \Lambda \pi^-$ decays, remained.

The neutral decays of the Λ were then selected by requiring:

- a neutron-induced shower in the LAD;
- one or two photon showers in the LAD or in the LG.

Late $\Lambda \rightarrow p\pi^-$ decays (downstream of hodoscope H3) were rejected by asking that no charged track be associated with a hadronic shower in the LAD (the π^- from the Ξ^- decay could not reach the LAD). At this stage, we were left with 190,000 events.

4. Analysis of the Λ Neutral Decays: Selection of $\Lambda \rightarrow n\gamma$ Candidates

The $\Lambda \rightarrow n\gamma$ decays were selected from the one-photon events, most of which were in fact due to the decays $\Lambda \rightarrow n\pi^0$ in which one of the photons had escaped detection for various reasons: these included incomplete coverage of the solid angle, conversion of the photon into an e^+e^- pair, inefficiencies of the detectors or of the reconstruction program.

Events with two detected photons, identified as $\Lambda \rightarrow n\pi^0$ decays, were used to calibrate the neutral particle detectors, to determine their efficiencies and to check the parameters of the simulation program. They also allowed a simulation of one-photon events with real events, as will be seen in Sect. 5.1. However, they were not used for normalisation of the branching ratio, since pattern recognition problems for 3-shower events are significantly different from those for 2-shower events.

The kinematics of $\Lambda \rightarrow n\gamma$ decays in our apparatus are such that 76% of the photons are expected to be found in the LAD, as opposed to only 15% in the lead glass array. On the other hand, only 14% of the $\Lambda \rightarrow n\pi^0$ decays have one photon in the LAD and none in the lead glass array. Therefore, the background due to $\Lambda \rightarrow n\pi^0$ events was significantly reduced at the price of a small loss in $\Lambda \rightarrow n\gamma$ events, by using only the events with exactly one photon in the LAD and none in the LG.

This procedure relies on a precise knowledge of the acceptances and of the efficiencies of various part of the apparatus, for the two Λ decay channels considered, and therefore on a detailed simulation of the experiment.

4.1. Simulation of the Experiment

A Monte Carlo program generated the chain of decays $\Xi^- \rightarrow \Lambda\pi^-$, $\Lambda \rightarrow n\gamma$, or $\Lambda \rightarrow n\pi^0$, $\pi^0 \rightarrow \gamma\gamma$, with the known life-times of the Ξ^- and Λ . The Ξ^- beam was assumed to be unpolarized, since it was produced close to zero degrees. The longitudinal polarisation of the Λ and the resulting asymmetry of the decay $\Lambda \rightarrow n\pi^0$ were taken into account, as well as the precession of the Λ magnetic moment in the magnetic field of SM1. The effects of a possible non-zero value of $\alpha_{\Lambda \rightarrow n\gamma}$ were found to be negligible.

Fig. 4. Distribution of the $n\gamma\gamma$ effective mass (histogram). The Monte Carlo distribution for the decay $\Xi^- \rightarrow \Lambda + \pi^-$, $\Lambda \rightarrow n + \pi^0$, $\pi^0 \rightarrow \gamma\gamma$ (curve) is normalized to the total number of events

Secondary particles were tracked through the apparatus. For the charged particles, normally-distributed errors were added to the momenta and directions. The inefficiencies of the chambers were taken into account.

For the neutral particles, the coordinates of the impact point and (in the case of a photon) the energy were assigned normal errors corresponding to the measured resolution. No attempt was made to simulate in detail the development of the showers in the LAD.

The effect of photon conversion in the material upstream of the LAD was also simulated. This involved computing the probability of conversion and the probability of detecting the electron/positron shower.

The simulated events were subjected to the same triggering conditions, geometrical cuts and kinematical criteria as the real events. The quality of the simulation can be assessed by examining Figs. 2 and 3, which show the distribution of the decay angle and of the $\Xi^- - \pi^-$ missing mass for the full sample of reconstructed Ξ^- decays, and Fig. 4, which shows the effective ($n\gamma\gamma$) mass for the two-photon event sample.

4.2. Efficiency of the Liquid Argon Detector

A calculation based on the number of absorption lengths in the LAD predicts that 96% of the neutrons and 94% of the charged pions will produce a shower. However, because of losses resulting from pulse-height cuts and pattern recognition inefficiencies, the probability of observing showers in the LAD, as measured for charged pions from the beam, was $(88 \pm 4)\%$.

Fig. 5. **a** Distribution of the projected distance (along x axis) between the neutron and the nearest photon shower axes, in the LAD. The arrow indicates the position of the cut. **b** Distribution of the projected distance (along x axis) between two photon shower axes, in the LAD. The Monte Carlo calculations (curves) are normalized to the same total number of events. Similar distributions are observed along the y axis

The pulse-height cuts also affected the detection of low energy photons (<0.5 GeV). However, the comparison of real and simulated events (one- or two-photon events) showed an additional and much more important loss of photons due to the geometrical overlap of the photon and neutron showers in one projection. This effect was particularly marked for distances less than 5 cm between the shower axes (Fig. 5a). The neutron was not affected by this loss, the combined shower being interpreted as a neutron shower by the pattern recognition program. A similar but less important effect resulted from the overlap of two photons (Fig. 5b). Furthermore, the pattern recognition program was not fully efficient in reconstructing photon showers with energy less than 6 GeV; this problem was aggravated by the presence of a neutron shower. Indeed, the reconstruction ef-

ficiency was observed to go down from $\sim 100\%$ at 6 GeV to less than 50% at 2 GeV.

Two further effects which could affect the photon reconstruction were a fluctuation in the neutron shower being interpreted as a photon, and an incorrect sharing of the measured energy between neighbouring photon and neutron showers. To suppress uncertainties due to the above effects we required a minimum photon energy of 4 GeV and a minimum projected distance between the photon and the neutron shower axes of 80 mm. We also required that the photon energies measured in the two projections agreed within 2 GeV. All these effects were included in the Monte Carlo program.

It is estimated that, as a result of the various inefficiencies, about one half of the one-photon events have a second undetected photon in the LAD. This point is discussed further in Sect. 5.1.

4.3. Selection of the $\Lambda \rightarrow n\gamma$ Candidates

We now discuss the separation of the $\Lambda \rightarrow n\gamma$ decays (*good events*) from the more abundant $\Lambda \rightarrow n\pi^0$ decays with only one photon detected (*fake events*). Note that the measured quantities are the following:

- the momenta and directions of the Ξ^- and π^- (these define the momentum and direction of the Λ),
- the coordinates of the impact point of the neutron in the LAD,
- the coordinates of the impact point of the photon, and its energy.

From these quantities, and under the assumption of a $\Lambda \rightarrow n\gamma$ decay, we calculated the position of the Λ decay point along the reconstructed Λ trajectory. This determined the directions of the neutron and of the photon. The neutron energy was obtained from the global energy balance.

A selection procedure consisting of fitting all the events to the hypothesis $\Lambda \rightarrow n\gamma$ and then selecting the “good” events on the basis of a χ^2 value was not sufficient in our case: applying this procedure to the $\Lambda \rightarrow n\pi^0$ Monte Carlo events showed that a large proportion of these events satisfied the $\Lambda \rightarrow n\gamma$ hypothesis.

Instead we based our selection on the distributions of the photon energy E_γ and of the coordinate Z_Λ of the calculated Λ decay point. The E_γ spectrum of $\Lambda \rightarrow n\gamma$ decay extends up to 29 GeV, while that of $\Lambda \rightarrow n\pi^0$ extends to only 23 GeV (Fig. 6). For fake events, the value of Z_Λ , as calculated above, is clearly not the position of the real decay point but is, on average, 8 m downstream of this point (Fig. 7).

Before comparing the experimental and MC samples, the events were subjected to further cuts.

Fig. 6. Distribution of the photon energy (in the lab system) for the one-photon events (histogram). The corresponding Monte Carlo distributions for fake events (solid line) and for good events (dashed line) are normalized to the number of events above 4 GeV. The arrow indicates the position of the cut

Fig. 7. Distribution of the quantity Z_A defined in Sect. 4.3 (histogram). The corresponding Monte Carlo distributions for fake events (solid line) and for good events (dashed line) are normalized to the total number of events observed

We rejected events in which the Λ transverse momentum as calculated from the Ξ^- decay did not match the Λ transverse momentum deduced from the momenta of the neutral particles. Events where Z_A was upstream of the Ξ decay vertex were also rejected.

After all the above cuts, 13,594 events remained. The distributions of E_γ and Z_A for this sample are plotted in the histograms of Figs. 6 and 7. The two Monte Carlo curves are normalized to the total number of events in the data histograms. The experimental spectra are well represented by the Monte Carlo calculations for fake events ($\Lambda \rightarrow n\pi^0$, $\pi^0 \rightarrow \gamma(\gamma)$ decays). Good events ($\Lambda \rightarrow n\gamma$ decays) are not pro-

Fig. 8a-c. Event distribution in the Z_A – E_γ plane, where E_γ is the photon energy in the lab. system, and the quantity Z_A is defined in the text (Sect. 4.3). The vertical scale is such that the successive steps contain respectively 1–2, 3–4, 5–6, 7–9, 10–15, 16–24, 25–41 events. **a** Fake events (Monte Carlo) normalized to the number of real events. The limit of the signal region is shown. **b** Good events (Monte Carlo). **c** Data (13,594 events)

minent in this representation, indicating that the branching ratio is of the order of 10^{-3} or less.

Consider the distribution of the events as a function of Z_A and E_γ . Figure 8a shows the isometric plot of this distribution for fake events, as calculated by Monte Carlo, normalized to the number of real events. Figure 8b shows the Monte Carlo distribution for good events ($\Lambda \rightarrow n\gamma$ decays). The comparison of these two figures clearly shows a region at small Z_A and high E_γ which is kinematically accessible to good events but free of background from

Fig. 9a and b. Distribution in the $Z_A - E_\gamma$ plane, for two-photon events treated as one-photon events. For the vertical scale, see the caption of Fig. 8. **a** Two photons seen in the LAD (14,846 entries). **b** One photon seen in the LAD, one in the LG (5,791 events)

fake events. The distribution of the experimental data is shown in Fig. 8c. In this figure, the above mentioned region appears to contain events in excess of what is expected from fake events.

The “signal region” was defined by the following conditions:

$$\begin{aligned} Z_A &< 8 \text{ m} && \text{for } E_\gamma < 16 \text{ GeV}, \\ Z_A &< 5/6(E_\gamma - 16) + 8 \text{ m} && \text{for } 16 \leq E_\gamma \leq 22 \text{ GeV}, \\ Z_A &< 13 \text{ m} && \text{for } E_\gamma > 22 \text{ GeV}. \end{aligned}$$

The boundary of the signal region is indicated on Figs. 8 and 9. They are 42 “candidates” in this region.

5. Results

5.1. Evaluation of the Background Among the Candidates

The Monte Carlo calculation predicted a background of 11 fake events in the signal region. However, these background events belong to the tail of

the distribution of fake events, and their number is very sensitive to effects not included in the Monte Carlo simulation, such as the presence of non-Gaussian errors. It was therefore important to have at our disposal alternative, independent methods, based on the data themselves, to evaluate the background.

One such method relied on a “visual examination” of each of the 42 candidates. A picture of the event was drawn by computer, showing the hits in the chambers and the reconstructed charged particle trajectories. A display of the neutral particle detectors was printed, showing the hit channels together with the signal amplitudes. The picture was examined to check that no background source was visible, such as an undetected photon conversion, an accidental track or an interaction in some part of the spectrometer. No background of this sort has been identified. The detector display was scanned for showers which could have been missed by the pattern recognition program. From this visual examination, we found 11 events with an additional small signal in the LAD, which could be interpreted as a second photon; the effective mass of the two photons was calculated and in 8 cases was found to be compatible with the π^0 mass.

We have checked the efficiency of this procedure by comparing the results of several observers on a sample much larger than the 42 candidates. This efficiency was found to be close to 100%. Furthermore, the different observers found the same 11 spurious events in the candidate sample. From now on we consider these 11 events as background, 8 of them being definitely identified as $\Lambda \rightarrow n\pi^0$ decays, and we are left with 31 candidates.

A fraction of the background due to $\Lambda \rightarrow n\pi^0$ decays was not directly accessible by this scanning method, either because one of the photons missed both detectors, or because its shower overlapped in space the neutron shower. In order to evaluate this fraction, we have scanned the display of all the events (135) in a region of the $Z_A - E_\gamma$ plot adjacent to the signal region, where we know that the majority of events are fake events. We found 67 events with an additional shower, of which 49 have an effective $\gamma\gamma$ mass in agreement with the π^0 mass. For 4 more events, the neutron shower was very wide and overlapped the photon shower, making the interpretation of the event unreliable. Knowing that the fraction of “additional shower” events with a reconstructed π^0 is the same in this sample (49/67) and in the candidate sample (8/11), and assuming that the proportion of fake events which show an additional photon in the visual scanning is the same for the two samples, we calculated a background of

7.3 $\Lambda \rightarrow n\pi^0$ decays among the remaining 31 candidates. This calculation made use of the relative acceptance of genuine $\Lambda \rightarrow n\gamma$ events in the two regions, as determined by Monte Carlo.

Another method of evaluating the background due to fake events was based on the study of the real two-photon events. It consisted of ignoring one of the photons and treating the remaining $n-\gamma$ combination as a one-photon event. The $Z_A - E_\gamma$ plots of these pseudo-background events are shown in Fig. 9. Figure 9a corresponds to the subsample of events with two photons in the LAD (2 entries per real event), and Fig. 9b to the subsample of events with one photon in the LG and one in the LAD, the latter being the one used in the $n-\gamma$ combination (one entry per real event). On these figures, we find respectively 16 and 13 events in the signal region. Of these 29 events, 12 are unambiguous $\Lambda \rightarrow n\pi^0$ decays. The remaining ones are presumably also $\Lambda \rightarrow n\pi^0$ decays, badly reconstructed since they fall outside the allowed kinematical region. Correcting for the different sample sizes and for the respective geometrical acceptances of the detectors, we estimated 19 background events among our 42 candidates by this method.

Of the three methods used to estimate the background from $\Lambda \rightarrow n\pi^0$ decays, the first one (the Monte Carlo calculation) can give only a lower limit, for the reasons mentioned above. The results of the other two methods are in very good agreement. We have chosen to use the result of the visual scanning method since it is based on the actual sample of events which contains the signal, whereas the method based on the two-photon events uses a different (although similar) sample.

In the $Z_A - E_\gamma$ plot, the pseudo-background events, as well as the candidates which have been rejected by visual scanning, are more concentrated near the border of the signal region than the remaining candidates, as expected for a background from $\Lambda \rightarrow n\pi^0$ decays.

We have considered possible sources of background other than $\Lambda \rightarrow n\pi^0$ decays. Late $\Lambda \rightarrow p\pi^-$ decays (downstream of hodoscope H2) where the proton and pion have escaped detection by the chambers and one hadronic shower has been mistaken for a photon shower, could simulate a $\Lambda \rightarrow n\gamma$ decay. No event of this kind (in particular no proton candidate) has been found in the visual examination of a large sample of events. Decays $\Lambda \rightarrow n\pi^0$, followed by $\pi^0 \rightarrow e^+ e^- \gamma$, where the e^+ and e^- escape detection, have essentially the same kinematics as the fake events ($\pi^0 \rightarrow \gamma\gamma$) and contribute much less than 1% of the background. Finally, a background photon (produced for instance by interaction of the

π^- from the Ξ^- decay), combined with the neutron from a $\Lambda \rightarrow n\pi^0$ decay, the 2 photons from the π^0 escaping from both the LG and the LAD, is extremely unlikely to result in a $\Lambda \rightarrow n\gamma$ candidate, in view of the tight kinematical constraints applied.

Thus, since the only significant source of background is from fake events, the total estimated background among the 31 remaining candidates is 7.3. We are therefore left with 23.7 events which we attribute to $\Lambda \rightarrow n\gamma$ decays.

5.2. Calculation of the Ratio

$$\Gamma(\Lambda \rightarrow n\gamma)/\Gamma(\Lambda \rightarrow n\pi^0)$$

The ratio $R = \Gamma(\Lambda \rightarrow n\gamma)/\Gamma(\Lambda \rightarrow n\pi^0)$ is computed as follows:

$$R = \frac{N(\Lambda \rightarrow n\gamma)}{N(\Lambda \rightarrow n\pi^0)} \times \frac{A(\Lambda \rightarrow n\pi^0)}{A(\Lambda \rightarrow n\gamma)}$$

where:

$N(\Lambda \rightarrow n\gamma)$ is the number of genuine $\Lambda \rightarrow n\gamma$ decays in the signal region: $N = 23.7$. This number has the following independent statistical errors: $\pm\sqrt{31}$ from the observed number of events in the signal region not rejected by the visual scanning, and ± 2.5 from the estimate of the remaining background (7.3 events), which was obtained from the scanned events outside the signal region. The total error is therefore ± 6.1 ;

$N(\Lambda \rightarrow n\pi^0)$ is the number of $\Lambda \rightarrow n\pi^0$, $\pi^0 \rightarrow \gamma\gamma$ decays with 1 photon detected in the LAD and reconstructed by the pattern recognition program, and satisfying all the geometrical and kinematical conditions. This number is obtained by subtracting from the 13,594 events quoted in Sect. 4.3 a number of $\Lambda \rightarrow n\gamma$ events estimated from the number observed in the signal region: $N = 13,509$;

$A(\Lambda \rightarrow n\gamma)$ and $A(\Lambda \rightarrow n\pi^0)$ are the corresponding acceptances calculated by the Monte Carlo program: $A(\Lambda \rightarrow n\gamma) = 0.065$ and $A(\Lambda \rightarrow n\pi^0) = 0.106$. The acceptance for the $n\gamma$ mode refers to the signal region while the acceptance for fake events refers to the whole $Z_A - E_\gamma$ plot.

The result is: $R = (2.86 \pm 0.74) \times 10^{-3}$, where the error is only statistical.

We have checked the stability of this result with respect to reasonable changes in the various cuts applied in the event selection, for instance changing the cuts on the distance between shower axes from 8-6 cm or relaxing the kinematical criteria used to identify $\Lambda \rightarrow n\gamma$ events. We have varied the values of the parameters of the energy calibration curve of the LAD within the uncertainties; in the worst case, we obtained a variation of 10% of the branching ratio.

Table 1. Ratio $\Lambda \rightarrow n\gamma/\Lambda \rightarrow n\pi^0$ for various signal regions

Signal region	Number of events				Ratio with statistical error, in units of 10^{-3}
	Total	Background	Signal (scanning)	Scanning 2γ -events	
1	42	18	19	24	2.86 ± 0.74
2	54	32	29	22	2.25 ± 0.73
3	27	10	11	17	3.25 ± 0.96

Definition of the signal regions

$$1) \begin{cases} Z_A < 8 \text{ m} & \text{for } E_\gamma < 16 \text{ GeV} \\ Z_A < 5/6(E_\gamma - 16) + 8 \text{ m} & \text{for } 16 < E_\gamma < 22 \text{ GeV} \\ Z_A < 13 \text{ m} & \text{for } E_\gamma > 22 \text{ GeV,} \end{cases}$$

2) the boundary shifted by $+0.5 \text{ m}$ in Z_A and -0.25 GeV in E_γ ,

3) the boundary shifted by -1 m in Z_A and $+0.5 \text{ GeV}$ in E_γ .

We have also considered the effect of changing, within reasonable limits, the various efficiencies introduced in the Monte Carlo program (in particular the LAD efficiency). We observe variations of at most 7 % of the calculated acceptances.

We have verified that using different conventions in the visual scanning method, for instance rejecting only events with a reconstructed π^0 from the candidate sample, never changed the signal by more than 8 %.

As a check of our understanding of the shower reconstruction and separation, we have selected a subsample of events where the neutron shower is initiated in block C of the LAD. Thereby we expect to reduce significantly the problems due to the interference between neutron and photon showers. This selection decreases the acceptance to 34 % of its initial value, the number of candidates decreases from 42 to 15 (36 %) and the number of events rejected by the visual scanning from 11 to 4 (36 %). These variations are fully compatible.

Finally, as a check of consistency, we have evaluated the background and the branching ratio for two other signal region boundaries, one on either side of the standard boundary. Table 1 gives the definition of the boundaries, together with the respective numbers of candidates, background events and signal. As can be seen in the table, the background estimates from the two methods are in good agreement with each other, and the results obtained for the branching ratio are compatible within the errors.

All this considered, we were led to introduce a systematic error of 20 % on the branching ratio.

5.3. Discussion

In this experiment, the $\Lambda \rightarrow n\gamma$ decay has been observed for the first time. The ratio $R = \Gamma(\Lambda \rightarrow n\gamma)/\Gamma(\Lambda \rightarrow n\pi^0)$ is found to be:

$$R = (2.86 \pm 0.74 \pm 0.57) \times 10^{-3}$$

where the first error is statistical and includes the statistical error on the background estimate, and the second error includes systematic uncertainties due to the apparatus efficiency and to the background estimate.

The radiative decay branching ratio may be calculated, using the world average value of the $\Lambda \rightarrow n\pi^0$ branching ratio [5]:

$$\begin{aligned} \text{BR}(\Lambda \rightarrow n\gamma) &= R \times \frac{\Gamma(\Lambda \rightarrow n\pi^0)}{\Gamma(\Lambda \rightarrow \text{all})} \\ &= (1.02 \pm 0.33) \times 10^{-3}. \end{aligned}$$

where the statistical and the systematic errors have been added quadratically.

Our result can be compared with the theoretical predictions listed in Table 2. The calculation based on a one-quark transition [6] is clearly ruled out.

Table 2. Theoretical predictions for the branching ratios of radiative decays of hyperons (in units of 10^{-3})

References	$\Sigma^+ \rightarrow p\gamma$	$\Lambda \rightarrow n\gamma$	$\Xi^0 \rightarrow \Sigma^0\gamma$	$\Xi^0 \rightarrow \Lambda\gamma$	$\Xi^- \rightarrow \Sigma^-\gamma$	$\Omega^- \rightarrow \Xi^-\gamma$
[6]	(1.24) ^a	22	9.1	4.0	11	41
[7]	(1.24) ^a	5.97	1.48	1.80	(1.20) ^a	0.6
[7]	(1.24) ^a	1.70	0.23	1.36	(1.20) ^a	0.6
[8]	(1.17) ^a	0.26	1.4	0		
[8]	(1.17) ^a	0.82	1.1	0.12		
[9]	0.34 ± 1.25	1.9 ± 0.8				
[10]	$0.92^{+0.26}_{-0.14}$	0.62	7.2	3.0		
[11]	$0.82^{+0.41}_{-0.31}$	1.02	5.87	2.29		
[12/13]	0.66	1.5	10	15	0	

^a Used as input

Most of the predictions based on the two-quark transitions [7, 8] or on pole models [9–13] are compatible with our result and with the value of the $\Sigma^+ \rightarrow p\gamma$ branching ratio, when one takes into account the experimental error and the uncertainties of the theoretical calculations as well. Finally it is interesting to notice that our result is close to the lower limit calculated on the basis of the unitarity principle, 0.85×10^{-3} [9, 14].

References

1. S.F. Biagi et al.: Z. Phys. C – Particles and Fields **28**, 495 (1985)
2. P. Jacot-Guillarmod: PhD Thesis, University of Lausanne (1984). Unpublished
3. M. Bourquin et al.: Phys. Lett. **B 153**, 13 (1979)
4. P. Mühlemann: UGVA-DPNC 1983/03-111 University of Geneva. Unpublished
5. Particle Data Group: Rev. Mod. Phys. **56**, No 2, Part 2 (1984)
6. F.J. Gilman, A.B. Wise: Phys. Rev. **D 19**, 976 (1979)
7. A.N. Kamal, R.C. Verma: Phys. Rev. **D 26**, 190 (1982)
8. P. Eckert, B. Morel: UGVA 103-340 (1982) University of Geneva. Unpublished
9. G. Farrar: Phys. Rev. **D 4**, 212 (1971)
10. M.B. Gavela et al.: Phys. Lett. **101 B**, 417 (1981)
11. K.G. Rauh: Z. Phys. C – Particles and Fields **10**, 81 (1981)
12. M. Scadron, L. Thebaud: Phys. Rev. **D 8**, 2190 (1973)
13. M. Scadron, M. Visnesu: Phys. Rev. **D 28**, 1117 (1983)
14. V.I. Zakharov, A.B. Kaidolov: Sov. J. Nucl. Phys. **5**, 259 (1967)