

### Measurement of the $\Lambda \rightarrow n + \gamma$ Branching Ratio

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The branching ratio for the  $\Lambda$  weak radiative decay has been measured to be  $B(\Lambda \rightarrow n + \gamma) / (\Lambda \rightarrow \text{anything}) = [1.78 \pm 0.24(\text{stat}) \pm 0.16(\text{syst})] \times 10^{-3}$ . A low-energy kaon beam was used to produce the  $\Lambda$  hyperons via the reaction  $K^- + p \rightarrow \Lambda + \pi^0$  at rest. Photons from the signal channel and  $\pi^0$  decay were detected with a NaI(Tl) array. The final spectrum contains 287 events after background subtraction, an order of magnitude more events than from the only previous measurement.

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Weak radiative hyperon decays ( $B \rightarrow B' + \gamma$ ) and non-leptonic hyperon decays ( $B \rightarrow B' + \text{meson}$ ) are closely related. While both have been studied extensively for many years, several problems remain. In particular, there is no satisfactory explanation of the empirically well established  $|\Delta I| = \frac{1}{2}$  rule in  $\Delta S = 1$  decays [1], nor is there an adequate understanding of the relative phases and magnitudes of the parity-violating and parity-conserving amplitudes [2]. As the theory of photon emission is better grounded than that of pion emission, the radiative decays should provide more reliable tests of the theories.

A number of new experiments have produced results within the last few years [3,4]. Of six experimentally accessible weak radiative decay channels, the branching ratio has been determined for five (mostly with large uncertainties), and for the sixth an upper limit has been established. The asymmetries are less well known, and only in the channel  $\Sigma^+ \rightarrow p\gamma$  is it well measured. In the only previous investigation of  $\Lambda \rightarrow n\gamma$ , Biagi *et al.* [5] observed 23.7 events from which a branching ratio of  $(1.02 \pm 0.33) \times 10^{-3}$  was determined. We report here on a measurement of the  $\Lambda \rightarrow n\gamma$  branching ratio based on 287 events.

Protons of 24 GeV/c from the Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS) produced a 680-MeV/c  $K^-$  beam in the twice-separated beam line LESB-II. Figure 1 shows a schematic view of the apparatus. Incident  $K^-$  were identified with lucite Čerenkov and scintillator  $dE/dx$  counters. The  $K^-$  was slowed in a copper degrader and stopped in a 4.9-l liquid-hydrogen target. A scintillator hodoscope was placed immediately in front of the target. Two layers of

plastic veto counters surrounded the target and were used to reject events with secondary charged particles. Neutrals from  $K^-p$  reactions were detected in the Crystal Box (CB) [6], a large modular array of 396 optically separated NaI(Tl) crystals covering about  $2\pi$  solid angle. The trigger required an incident kaon, no detected charged decay products, and a hardware sum of at least 300 MeV deposited in the CB.

Cluster-finding algorithms were used to identify photons in the CB. By summing over all crystals in a cluster the energy and impact point of the  $\gamma$  were determined. The 129.4-MeV photons from  $\pi^-p \rightarrow n\gamma$  at rest were used for energy and detector line-shape calibration. For centrally located crystals an energy resolution of 7%

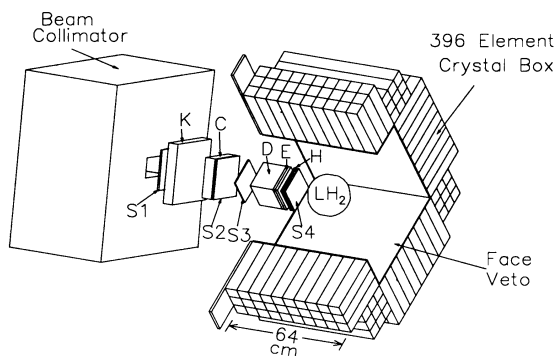


FIG. 1. Schematic view of the apparatus showing a cut away view of the Crystal Box. The beam line elements consist of four plastic scintillators (S1-S4), two Čerenkov counters (K,C), the degrader (D), two  $dE/dx$  counters (E), a hodoscope (H), and the liquid-hydrogen target (LH<sub>2</sub>).

FWHM at 129.4 MeV was obtained. In edge and corner crystals the resolution was worse ( $\approx 12\%$ ) due to shower leakage. Neutron interactions in the CB were investigated by studying the channels  $\pi^-d \rightarrow nm$  and  $K^-p \rightarrow \Sigma^-\pi^+$ ,  $\Sigma^- \rightarrow n\pi^-$ . By exploiting the fact that neutron interactions have more radially confined showers, a partial  $n\text{-}\gamma$  particle identification was possible. The  $x$  and  $y$  coordinates of the vertex were given by the beam hodoscope while the  $z$  coordinate was assumed to be the center of the target.

$\Lambda$  production was tagged by detecting the 288-MeV  $\pi^0$  produced in the reaction  $K^-p \rightarrow \Lambda\pi^0$  at rest (probability 6.7%). Using the  $\pi^0$  to determine the  $\Lambda$  direction, we transformed the energy of the photon emitted in the decay  $\Lambda \rightarrow n\gamma$  to the rest frame of the  $\Lambda$ . The photon energy in this frame is 162 MeV. Although the channel  $K^-p \rightarrow \Sigma^0\pi^0$ ,  $\Sigma^0 \rightarrow \Lambda\gamma$  has a higher probability (27.3%), it is not as suitable for analysis since it requires detecting 4 photons in the final state which has a more complicated topology, and there is a 4-photon background channel  $K^-p \rightarrow \Lambda\pi^0$ ,  $\Lambda \rightarrow n\pi^0$ . In this paper we restrict our discussion to the analysis of the 3-photon channel.

A first selection of events had the following properties: (1) only one hit in  $x$  and  $y$  in the hodoscope, (2) no charge above pedestal in any veto counter, (3) no events with clusters in which the high-pulse-height crystal was an edge or corner crystal, (4) exactly 3 photons and  $\leq 1$  neutron, (5) proper timing between photons and the incoming  $K^-$ , (6) 2 photons reconstructible as a  $\pi^0$  with invariant mass and energy restricted to 110–155 MeV/ $c^2$  and 270–295 MeV, respectively, and (7) no other combination reconstructible as a  $\pi^0$ . Only loose cuts were placed on the missing mass of the neutron as such a cut is equivalent to an energy cut on the weak radiative decay photon and the result of such a cut is to remove the normalization rather than clean up the signal region. These cuts reduced the initial sample of  $16 \times 10^6$  events on tape to  $3.5 \times 10^5$  events.

The majority of events remaining came from the prolific nonradiative  $\Lambda$  decay channels: (i)  $K^-p \rightarrow \Lambda\pi^0$ ,  $\Lambda \rightarrow n\pi^0$  and (ii)  $K^-p \rightarrow \Sigma^0\pi^0$ ,  $\Sigma^0 \rightarrow \Lambda\gamma$ ,  $\Lambda \rightarrow n\pi^0$ . In channel (i) the signal could be mimicked if one photon escaped detection. The single-photon spectrum in the  $\Lambda$  rest frame is peaked mainly below 140 MeV. The spectrum drops off sharply above 140 MeV, but still has a tail due to wrong combinations and the detector response extending into the signal region (140 to 180 MeV), contributing about the same number of events to this region as the signal. Channel (ii) could conspire to have a topology similar to signal events through various combinations of missing or overlapping photon showers. A restriction on the minimum opening angle ( $\theta > 0.8$  rad) between all photon pairs reduced the relative contribution of this channel.

Pileup was a potential problem since it could extend the high-energy tail from  $\Lambda \rightarrow n\pi^0$  decay further into the signal region. To reduce pileup we limited the beam flux

to  $5 \times 10^5$  particles per second. To identify pileup events two analog-to-digital converters analyzed each crystal's pulse. The first determined the energy by integrating the entire pulse (250 ns for the shaped NaI signal), while the second sampled 50 ns of the leading edge. The ratio of these two was sensitive to the pulse arrival time (relative to that of the incoming kaon), and hence to pileup. Through an application of energy-dependent cuts on this ratio, the pileup background was reduced significantly. However, the separation between signal and pileup was not complete, so these cuts introduced a substantial systematic uncertainty (see below). After the overlapping shower and pileup cuts, a sample of  $1.2 \times 10^5$  events remained.

Background events produced in flight, in particular from charge exchange,  $K^-p \rightarrow \bar{K}^0n$ ,  $K_S^0 \rightarrow \pi^0\pi^0$ , were only partially removed by cuts on the  $dE/dx$  beam counters. As its cross section near threshold is not well known, and the momentum distribution of the kaons emerging from the degrader is uncertain, the relative rate for this channel had to be measured independently. This was accomplished by analyzing 4-photon events which could be reconstructed as a  $\pi^0\pi^0$  pair. Such events came almost exclusively from charge exchange, or channels (i) and (ii) mentioned above. By plotting the energy spectra of each  $\pi^0$ , the charge-exchange channel was clearly identifiable. The data were fitted with Monte Carlo (MC) simulated spectra and the rate of in-flight charge exchange measured to be  $(1.0 \pm 0.1)\%$  of the  $K^-$  stopping rate. By applying a tight cut,  $\theta_{\Lambda\gamma} > 1.2$  rad, where  $\theta_{\Lambda\gamma}$  was the angle between the  $\Lambda$  and the candidate weak radiative decay photon in the laboratory frame, we were able to eliminate most of the charge-exchange channel in the signal region. MC studies showed that this cut eliminated 99.5% of all charge exchange, while reducing the signal by 64%. In the signal region the amount of remaining charge-exchange background was estimated to contribute less than 1% of the events with a 90% confidence level. This led to the final sample of 43 200 events, of which about 900 were in the signal region.

To extract the branching ratio we fitted MC generated spectra to the data. A complete simulation of the apparatus, including shower development, was generated with the GEANT 3.13 package [7]. The production channels considered were (i)  $K^-p \rightarrow \Lambda\pi^0$ , (ii)  $K^-p \rightarrow \Sigma^0(\rightarrow \Lambda\gamma)\pi^0$ , (iii)  $K^-p \rightarrow \Sigma^+\pi^-$ , (iv)  $K^-p \rightarrow \Sigma^-\pi^+$ , (v)  $K^-p \rightarrow \Sigma^0(\rightarrow \Lambda\gamma)\gamma$ , (vi)  $K^-p \rightarrow \Lambda\gamma$ , and (vii)  $K^-p \rightarrow \bar{K}^0n$ . Channels (i) to (vi) were studied at rest and in flight whereas (vii) was only possible in flight. The  $\Lambda$  decayed into  $n\gamma$ ,  $n\pi^0$ , or  $p\pi^-$  and the  $\Sigma^+$  decayed into  $p\gamma$ ,  $p\pi^0$ , or  $n\pi^+$ .

The GEANT routines did a very good job of reproducing the detector response for electromagnetic showers, but performed relatively poorly for the low-energy neutrons. We measured the neutron detection efficiency in the CB to be about 30% using the neutrons from reaction  $\pi^-d \rightarrow nm$ , normalizing to the channel  $\pi^-d \rightarrow n\pi\gamma$  where

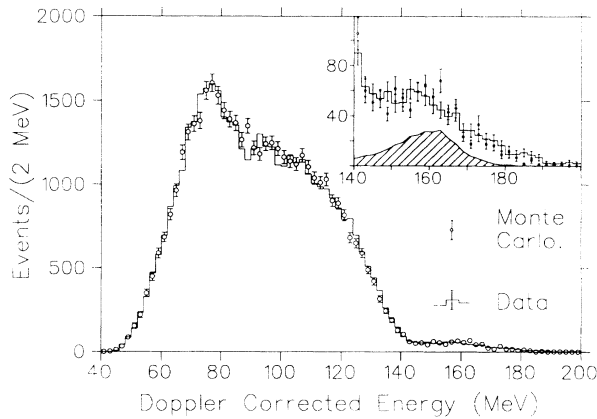


FIG. 2. The final fit to the data over the fitted range from 40 to 200 MeV. The signal region is shown in the inset. The shaded region shows the signal contribution determined by the fit.

the photon was easily identified. While MC simulation and data gave the same results for neutron detection efficiencies, they disagreed in their particle-type identification efficiencies. For MC neutrons, most of the energy was deposited in a single crystal, whereas the photon showers extended over many crystals. Hence MC neutrons and photons were easily distinguished by shower size. This was not observed to be true for real neutrons where 80% were misidentified as photons. This difference in identification efficiency was taken into account in the analysis by treating a weighted proportion of the MC identified neutrons as photons.

The experimental spectrum was fitted by the MC spectrum to determine the weak radiative decay branching ratio. The fit contained two parameters; an overall normalization, and the branching ratio. The relative contribu-

tion from the in-flight channel was held fixed at the result obtained from the  $2\pi^0$  fit. From the final fit (see Fig. 2), we determine the branching ratio to be

$$B\left(\frac{\Lambda \rightarrow n\gamma}{\Lambda \rightarrow \text{anything}}\right) = [1.78 \pm 0.24^{+0.14}_{-0.16}] \times 10^{-3},$$

where the first error listed is statistical and the second is systematic. The  $\chi^2$  per degree of freedom for the fit is 97.5/78. The statistical error was taken to be the MINOS error from the fitting routine MINUIT [8]. The  $\chi^2$  calculation included the errors from data and MC simulation. The MC error was as large as that of the data, but with the computing resources available it was impossible to generate a larger sample size. In addition, the fit was already being limited by the systematic differences between the MC simulation and the data so that in the best case of infinite MC statistics the overall error would be improved by at most 25%.

The MC spectrum included all channels studied, but effectively the normalization was dominated by channels (i) and (ii). The uncertainties in the branching ratios of these channels contributed  $\pm 0.8\%$  to the systematic errors. Background events arising from interactions outside the hydrogen target were corrected for by making target-empty subtractions. This subtraction was not exact as the stopping distribution was affected by the absence of hydrogen. We estimated that this led to a systematic uncertainty of  $\pm 2.9\%$ . After cuts, very few in-flight events remained so that fits leaving their contribution free found nonsensical values. By changing the in-flight strength by  $\pm 1\sigma$  the branching ratio varied by  $\pm 1.6\%$ . This was taken to be the systematic error from this source. Differing cut efficiencies between MC simulation and data contributed  $\pm 0.3\%$  to the uncertainty. These were dominated by the pileup cuts (pileup was not included in the MC simu-

TABLE I. Theoretical and experimental branching ratios (in units of  $10^{-3}$ ) and asymmetries.

	Ref.	Technique	Branching ratio	Asymmetry
Theory				
Farrar	[10]	Unitarity	$> 0.85$	
Farrar	[10]	Pole model	$1.9 \pm 0.8$	0.5
Gavela <i>et al.</i>	[15]	Pole model	0.62	-0.49
Gilman and Wise	[9]	Quark model	22	
Kamal and Verma	[14] A	Quark model	5.97	-0.96
Kamal and Verma	[14] B	Quark model	1.70	-0.45
Kamal and Verma	[14] C <sup>a</sup>	Quark model	2.18	-0.97
Żenczykowski	[11]	Symmetry	3.21	0.75
Żenczykowski	[12]	Fit	1.00	0.76
Liu	[16]	Pole/quark model	1.73	-0.94
Kao and Schnitzer	[17]	Skyrme model	1.23	0.98
Experiment				
Biagi <i>et al.</i>	[5]	$\Xi^-$ beam	$1.02 \pm 0.33$	
This work		Kaon beam	$1.78 \pm 0.24^{+0.14}_{-0.16}$	

<sup>a</sup>Calculated using the model of Ref. [14] and more recent data.

lation). These errors were estimated by observing the behavior of fits with various pileup cuts and beam rates. The overall MC gain was determined by fits to the data. The variation in this gain by  $\pm 1\sigma$  contributed an error of  $\pm 2.2\%$ .

Our result is to be compared with the previous result of Biagi *et al.* [5], which is  $[1.02 \pm 0.33] \times 10^{-3}$ , based on 23.7 events. The two results differ by about 1.7 standard deviations. They did not have a detailed MC simulation of the shower development in their calorimeter. Our experience with shower fluctuations leads us to believe that such a simulation may have led to a different interpretation of some events which were rejected on the basis of being associated with low-energy deposits elsewhere in the detector. This might account for the mild disagreement between our results.

Our result is compared with a representative sample of theoretical results collected in Table I. Our result agrees with studies of other weak radiative decays in ruling out the single-quark transitions considered by Gilman and Wise [9] as the dominant mechanism, and the value obtained in this experiment is significantly above the unitary limit calculated by Farrar [10]. Our results also suggest that the calculation by Żenczykowski [11] is inadequate to describe the data. In this calculation all parameters were fixed using the well-known nonleptonic decays and by relating these to the weak radiative decays through SU(6) symmetry arguments and the vector-meson dominance approach. In a more recent calculation [12] he used a two-parameter fit to avoid theoretical uncertainties and was able to fit the then existing world data. His prediction of  $1.0 \times 10^{-3}$  is low compared to our result, but he can also find satisfactory fits for branching ratios of about  $1.5 \times 10^{-3}$  if he takes into account the experimental error on  $\mu_{\Sigma\Lambda}$ , the  $\Sigma\Lambda$  transition magnetic moment [13]. Although our branching ratio is consistent with some calculations, for example, those of the one- and two-quark transitions considered by Kamal and Verma [14], these calculations do not agree with data for the other weak radiative decays. It is difficult with the present data to make conclusive statements about the success or failure of the theories although the method of vector-meson dominance and SU(6) by Żenczykowski does appear quite promising.

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- [1] J. O. Eeg, *Z. Phys. C* **21**, 253 (1984).
- [2] A. Le Yaouanc, O. Pène, J.-C. Raynal, and L. Oliver, *Nucl. Phys.* **B149**, 321 (1979).
- [3] S. Teige *et al.*, *Phys. Rev. Lett.* **63**, 2717 (1989).
- [4] C. James *et al.*, *Phys. Rev. Lett.* **64**, 843 (1990).
- [5] S. F. Biagi *et al.*, *Z. Phys. C* **30**, 201 (1986).
- [6] S. L. Wilson *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **264**, 263 (1988).
- [7] R. Brun *et al.*, CERN Report No. DD/EE/84-1, 1987 (unpublished).
- [8] F. James and M. Roos, *Comput. Phys. Commun.* **10**, 343 (1975).
- [9] F. J. Gilman and M. B. Wise, *Phys. Rev. D* **19**, 976 (1979).
- [10] G. R. Farrar, *Phys. Rev. D* **4**, 212 (1971).
- [11] P. Żenczykowski, *Phys. Rev. D* **40**, 2290 (1989).
- [12] P. Żenczykowski, *Phys. Rev. D* **44**, 1485 (1991).
- [13] P. Żenczykowski (private communication).
- [14] A. N. Kamal and R. C. Verma, *Phys. Rev. D* **26**, 190 (1982).
- [15] M. B. Gavela, A. Le Yaouanc, O. Pène, J.-C. Raynal, L. Oliver, and T. N. Pham, *Phys. Lett.* **101B**, 417 (1981).
- [16] Y. Liu, *Z. Phys. C* **45**, 345 (1989).
- [17] W. F. Kao and H. J. Schnitzer, *Phys. Rev. D* **37**, 1912 (1988).