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Precision Measurement of the Lifetime and Decay Branching Ratio of the Λ^0 Hyperon*

C. Baltay, A. Bridgewater,† W. A. Cooper, and M. Habibi
Columbia University, New York, New York 10027 and Brookhaven National Laboratory, Upton, New York 11973

and

N. Yeh
State University of New York, Binghamton, New York 13901
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A precision measurement of the Λ^0 lifetime τ_Λ and the branching ratio $R = (\Lambda \to p\pi^-)/(\Lambda \to \text{all})$ has been carried out. The results are $\tau_\Lambda = (2.54 \pm 0.04) \times 10^{-10}$ sec and $R = 0.646 \pm 0.008$. The errors include both the statistical errors and our estimate of the systematic errors.

I. INTRODUCTION

The decay branching ratio of the Λ^0 hyperon has often been cited as part of the evidence for the phenomenological selection rule $|\Delta I| = \frac{1}{2}$ for nonleptonic weak decays of baryons. This rule predicts, on the basis of isospin analysis of the initial and final states, that the value of $R = (\Lambda^0 \to p\pi^-)/[(\Lambda^0 \to p\pi^-) + (\Lambda^0 \to n\pi^0)]$ is $\frac{2}{3}$. Taking into account the difference in the available phase space for the two modes, the ratio is modified to 0.659. Radiative corrections[1] further modify this ratio to 0.674. An examination of the available data for this branching ratio, however, revealed that the most accurate results differed from each other by more than 2 standard deviations.[2,3]

This paper describes an experiment carried out to determine the Λ lifetime τ and the branching ratio R to an accuracy of about 1%. An effort has been made to minimize the sources of systematic errors. Using 20 000 pictures of the Brookhaven National Laboratory 30-in. hydrogen bubble chamber exposed to a beam of stopping K^- mesons, we collected a sample of more than 10 000 Λ^0-producing events. Subjecting this sample to the analysis described in the following sections, we obtained a mean life of $\tau = (2.54 \pm 0.04) \times 10^{-10}$ sec, and a branching ratio of $R = 0.646 \pm 0.008$.

II. EXPERIMENTAL METHOD

A. The K^- Beam

The low-energy separated beam[4] at BNL's Alternating Gradient Synchrotron was used in conjunction with the 30-in. hydrogen bubble chamber to obtain approximately 550 000 pictures of stopping K^-p reactions. These pictures were used for another experiment described elsewhere.[5] For the present study, we used 20 000 pictures from this exposure.

The beam consisted of two electrostatic separators which were tuned to 750-MeV/c K^- mesons with a momentum dispersion $\Delta p/p \sim 1\%$. Before their entrance into the bubble chamber, the K^- mesons were slowed down to ~250 MeV/c by 6 in. of copper. A beam flux of approximately ten stopping K^- mesons per picture was obtained, with about an equal number of π^- traversing the chamber. Since pions lose less energy in the copper degrader than charged K mesons, they entered the bubble chamber with a momentum of ~600 MeV/c.

B. Scanning and Measuring

The Λ hyperons were produced in the reactions

$$K^-p \to \Lambda^0\pi^0, \tag{1}$$

$$K^-p \to \Sigma^0\pi^0, \quad \Sigma^0 \to \Lambda^0\gamma. \tag{2}$$

It is kinematically possible to produce an additional neutral pion in reaction (1), but such reactions are severely inhibited by the limited phase space. Inasmuch as the Σ^0 decays electromagnetically into $\Lambda^0\gamma$, we can consider both reactions (1) and (2) as Λ^0-producing reactions.

When reaction (1) or (2) produced a Λ^0 which decayed into $n\pi^0$, a zero-prong event was observed. If, on the other hand, the Λ^0 decayed into $p\pi^-$ within the chamber, a zero-prong-plus-vee event would be observed. Scanners were instructed to search for zero-prong events with and without associated vees.

In order to achieve a high scanning efficiency, we restricted the scanning volume for zero-prong events to the central 20-cm × 20-cm region of the chamber (the chamber diameter is ~75 cm). For each zero-prong event found within this volume, vees were searched for within a small circle of 6-cm radius centered at the zero-prong vertex. This procedure of scanning first for zero-prong events and subsequently for associated vees was strictly adhered to, so that the scan was accomplished within the limited scanning volume with a minimum of bias with regard to the existence or nonexistence of a vee. The scan was performed on image-plane digitizing machines which projected approximately life-size pictures.

When a complete frame had been scanned, the events selected were measured by the scanner. Tracks were measured in all three views as 5-, 3-, or 2-point tracks depending on their projected lengths. The zero-prong events and vees within a frame were measured without requiring the scanner to associate them into events. Due to the low Q values in the production reactions (1) and (2), the Λ^0 emitted usually had low momentum so that the decay products also had small laboratory momenta. Consequently, most of the protons from the $\Lambda \to p\pi^-$ decay stopped in the bubble chamber, and a rather accurate proton momentum could be obtained from the range. Scanners were instructed to examine the positive decay tracks and set a special code if such tracks did not terminate within the bubble chamber.

All 20 000 pictures were subjected to two identical, independent scans in this manner, and the over-all scanning efficiency achieved was better than 99%. All zero-prong events found were then examined on a large magnification machine. The purpose of this study was to obtain an independent evaluation of the "quality" of the zero-prong events. This special scan eliminated zero-prong events caused by "late beam tracks," which appeared "faint" in the pictures because of their smaller bubbles. These events were eliminated in order to obtain a more uniform scanning efficiency, since a "late" zero-prong event without a vee would be more likely missed than a "late" zero-prong event with vee. This scan also eliminated zero-prong events if their bubble densities were inconsistent with those expected of stopping K^- mesons. This was to discard zero-prong events produced by in-flight π^- mesons. Stopping K^- mesons leave tracks with very high bubble densities, while 600-MeV/c π^- mesons leave tracks which are minimum ionizing. The distinction between the two is very clear and unambiguous on the scan table.

C. Analysis of Events

A total of ~14 000 events were measured. All events, including stopping K^- tracks with no associated vee, were processed through the geometric reconstruction program TVGP. Stopping K^- tracks which did not pass the "beam criteria" in azimuth and dip angles, or were out of the fiducial volume, were eliminated. Events with vees were subjected to kinematic fitting, using the program SQUAW, to the two possible interpretations

$$\Lambda \to p + \pi^-,$$

$$K^0 \to \pi^+\pi^-.$$

Events that made kinematic fits with good χ^2 confidence to the Λ or $\bar{K}^0$ interpretations were accepted as such. The distribution in the Λ mass, reconstructed from the measurements of the proton and the π^-, is shown in Fig. 1. The Λ momentum distribution is shown in Fig. 2. The peak at ~255 MeV/c is due to the two-body reaction (1); the events below 250 MeV/c are from reaction (2). There were no ambiguities between Λ and $\bar{K}^0$ decays at these low energies. There were only a total of 31 $\bar{K}^0$ fits in the whole experiment. Vees which made no satisfactory fit were remeasured and examined by a physicist, who either accepted the event as a good Λ decay or discarded it if the vee was either an e^+e^- pair, a scattered Λ, or from some alternative origin. Thus all events were positively disposed of, and no $\Lambda \to p + \pi^-$ decays were lost due to possible inefficiencies in the reconstruction on fitting programs.

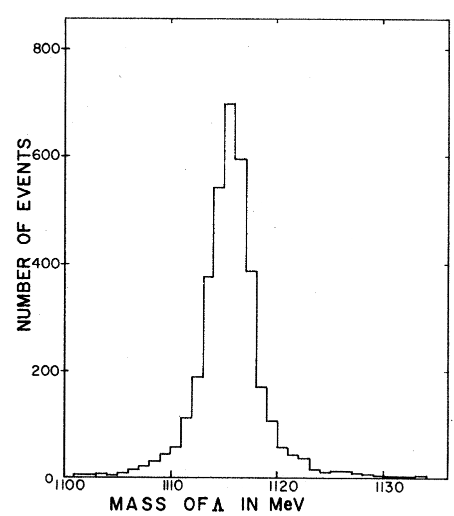

FIG. 1. The Λ mass reconstructed from the measured momenta and angles of the decay p and π^-.

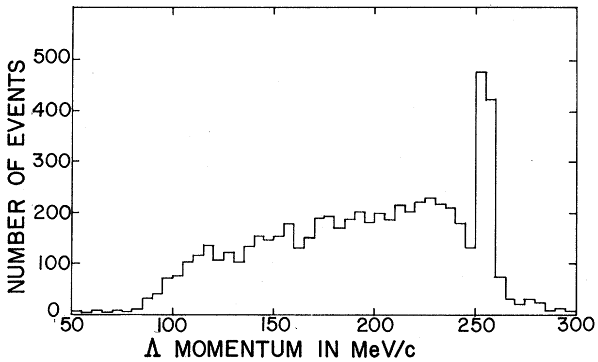

FIG. 2. Λ momentum distribution, weighted for detection efficiency.

All of the $\Lambda \to p + \pi^-$ events were subjected to the following selection criteria:

(a) The path length of the Λ is less than 5.0 cm.

(b) The path length of the Λ, projected on the front glass of the chamber, is larger than 0.2 cm.

(c) The projected length of the Λ-decay products, p or π^-, is larger than 0.2 cm.

(d) $|\sin\lambda| \leq 0.9$, where λ is the dip angle of the Λ^0.

A total of 4572 Λ decays passed these criteria. For each event, a weight was computed, equal to the reciprocal of the probability of having detected the event with the criteria above.

D. Background Events

The total number of zero-prong events processed is basically the total number of Λ^0's produced by K^- mesons in the experiment. There were two sources of zero-prong events, however, which did not produce Λ^0's. These were in-flight π^- interactions at ~600 MeV/c, and interactions of stopped π^- mesons. These backgrounds amounted to less than a few percent of the zero-prong events. The in-flight π^- interactions were eliminated by examining the beam-track bubble density (in the special scan mentioned above). Stopping K^-'s are very dense, while 600-MeV/c π^-'s are close to minimum ionizing; the distinction between the two is quite clear.

The stopping-π^- events can be eliminated by requiring agreement between momentum from the measured curvature of the beam track and momentum from range, assuming the track to be a stopping K^-: Figure 3 shows that this agreement is good for the stopping K^-'s and bad for stopping π^-'s. The two are quite well separated by a cut in $(P_{\text{curvature}} - P_{\text{range}})/\delta P = -3.0$, where δP is the error in the momentum from curvature. The stopping pions in this figure are not the zero-prong events, but a sample of pions undergoing π-μ-e decay,

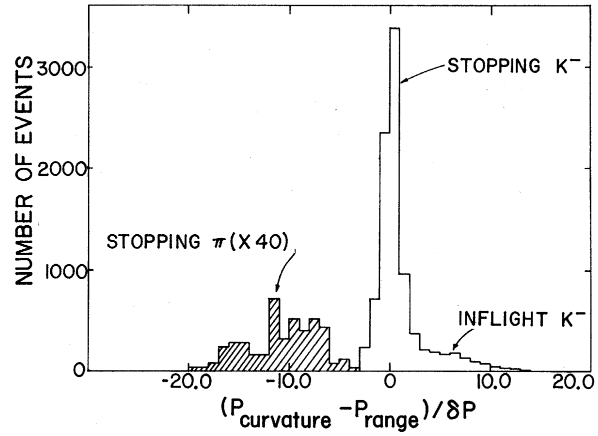

FIG. 3. Distribution in $(P_{\text{curvature}} - P_{\text{range}})/\delta P$ for zero-prong events, where $P_{\text{curvature}}$ is the momentum calculated from curvature and P_{range} is the momentum from range, assuming the track to be a stopping K^-. δP is the error on $P_{\text{curvature}}$. The shaded events are not zero-prong events but a sample of stopping π's which undergo $\pi \to \mu\nu$, $\mu \to e\nu\bar{\nu}$ decay in the chamber, measured to check our ability to identify stopping π's by the range-curvature comparison.

measured for the purpose of this comparison. For purposes of illustration, the number of stopping pions relative to the stopping K^-'s in this figure is much larger than is actually the case for stopping π^-'s producing zero-prong events.

About 5% of the zero-prong events are K^- interactions in flight. In principle these are not a problem since they produce Λ's like the stopping K^-'s. However, the in-flight K^-'s can produce $\bar{K}^0$'s by the charge-exchange reaction

$$K^- p \to \bar{K}^0 n . \tag{3}$$

This reaction is below threshold for stopping K^-'s. The number of $\bar{K}^0$'s produced can be calculated from the number of $K_1 \to \pi^+\pi^-$ decays which are identified from the kinematic fitting. It is, however, desirable to minimize this correction. This can be done by the range-curvature comparison. For in-flight events, the momentum from curvature exceeds the momentum from "range"; these events are responsible for the tail on the upper end of Fig. 3. A cut at 3.0 removes most of the in-flight K^- interactions, reducing the $\bar{K}^0$ production to 0.5% of the Λ production.

Photons converting into e^+e^- in the liquid hydrogen were not a background faking $\Lambda \to p + \pi^-$ decays, since at these energies the proton from Λ decay was below 300 MeV/c and very heavily ionizing, while the electron pairs were minimum ionizing. The e^+e^- pairs were discarded on the scan table unambiguously.

E. Scanning Losses

The entire film used in this experiment was scanned twice, with great emphasis placed on high efficiency. Comparison of the two scans showed that the combined efficiency of the two scans was 99.9%, i.e., only 1 out of 1000 vees was lost as a result of random scanning losses by both scanners. This, however, does not include systematic losses due to poor film quality, faint tracks, or systematic losses dependent on the topology of the events. The first one of these was eliminated by (a) selecting 20 000 pictures of the best quality out of a much larger exposure, and (b) a third scan through the film where faint tracks (tracks entering the chamber late) were removed from the sample, as were pictures with poor optical quality.

Systematic losses dependent on the topology of the Λ decay were studied by comparing various distributions of the observed events with a complete Monte Carlo simulation of the experiment. As expected, events were lost, or found with decreased efficiency, in the following cases:

(a) Λ decays too far from the K^- stop (more than 6 cm),

(b) Λ decays very close to the K^- stop (within 0.1 cm or so),

(c) the proton from the Λ decay being invisible or shorter than ~0.1 cm,

(d) the Λ having a large dip angle, i.e., heading directly toward or away from the cameras.

These regions of decreased scanning efficiency were eliminated altogether by the selection criteria imposed on all the events (see Sec. II C). The loss of events due to these selection criteria was corrected for by weighting the remaining events by the inverse of the probability of surviving these cuts. There were no significant losses of events outside of the regions removed by these criteria, as is demonstrated by the good agreement of the distribution of observed events with the Monte Carlo events in the Λ length (Fig. 4), proton length (Fig. 5), and the Λ dip angle (Fig. 6).

One other possible systematic loss might occur when the opening angle of the vee (angle between p and π^-) is close to 0° or to 180°. Figure 7 shows the comparison of the distribution in the opening angle between observed and Monte Carlo events. No loss is apparent at 0°, but there seems to be a loss near 180°. A correction of 94 ± 22 events was made, based on this distribution, to account for this loss.

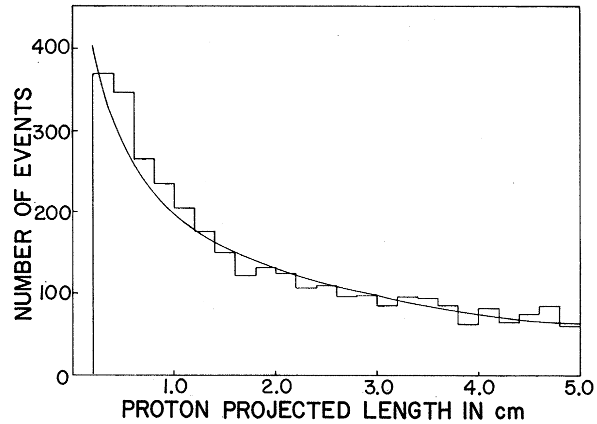

FIG. 5. Distribution in the projected length of the proton from Λ decay. The curve is the result from the Monte Carlo calculation.

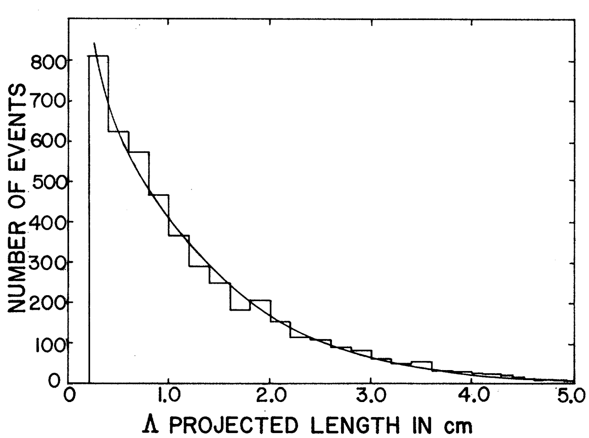

FIG. 4. Distribution in the Λ^0 projected length. The curve is the result from the Monte Carlo calculation.

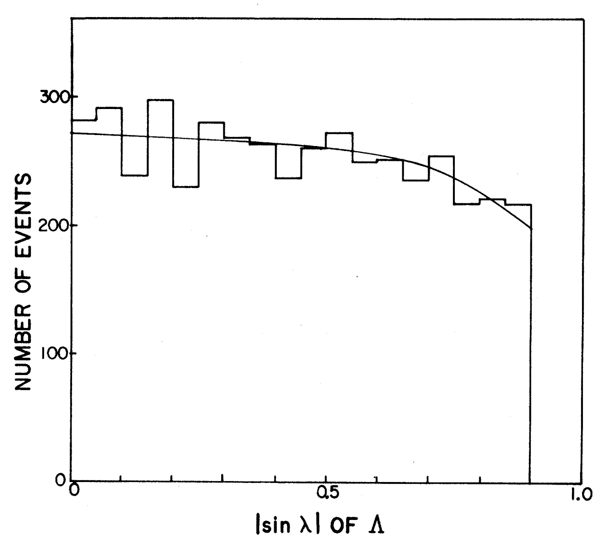

FIG. 6. Distribution in $|\sin\lambda|$, where λ is the dip angle of the Λ in the lab. The curve is the result of the Monte Carlo calculation.

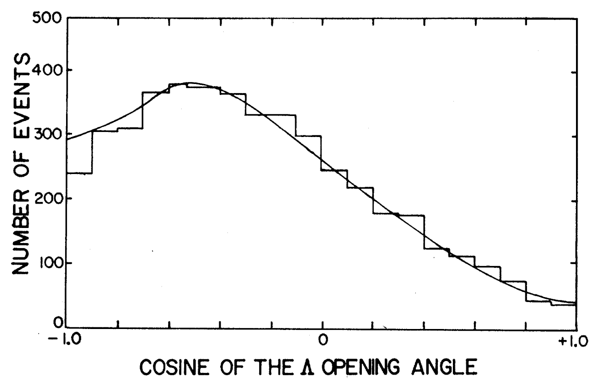

FIG. 7. Distribution in the cosine of the Λ-decay opening angle. The curve is the result of the Monte Carlo calculation.

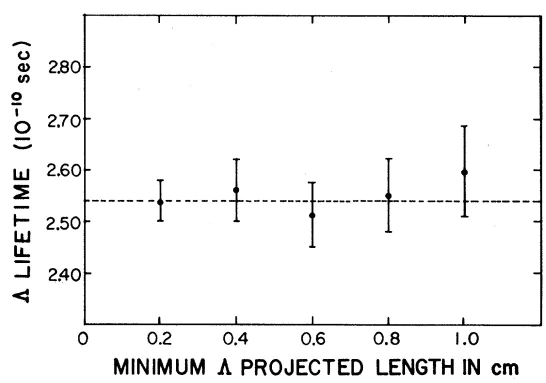

FIG. 8. Result of the Λ lifetime determination for various Λ projected length cuts.

III. RESULTS

A. The Λ^0 Lifetime

The sample of 4572 Λ^0 decays that survived the selection criteria described above was used to determine the Λ^0 lifetime. A maximum-likelihood analysis was performed. The likelihood function $\mathcal{L}(\tau)$ was calculated:

$$\mathcal{L}(\tau)=\prod_{i=1}^{4572}\frac{(1/\tau)\exp(-t_i/\tau)}{\exp(-t_i^{\min}/\tau)-\exp(-t_i^{\max}/\tau)}\,,$$

where

τ is the mean life of the Λ^0 at rest,

t_i is the observed proper time of the ith event,

$t_i^{\min}$ is the minimum proper time consistent with observation of the ith event,

$t_i^{\max}$ is the maximum proper time consistent with observation of the ith event.

The result of this analysis was

$$\tau=(2.54\pm0.04)\times10^{-10}\text{ sec}.$$

Detection biases dependent on the decay configuration of the Λ^0 do not affect this lifetime determination. But biases dependent on the distance of the decay point from the K^- stop would affect the above result. The comparison with Monte Carlo events, Fig. 4, gives us confidence that we have no such biases beyond the 0.2-cm minimum projected length cut. A further check of this was done by repeating the maximum-likelihood analysis with larger minimum-projected-length cuts. The lifetime did not vary appreciably for length cuts up to 1.0 cm, as is shown in Fig. 8. This indicates that there are no significant losses of Λ's beyond our minimum-projected-length cut of 0.2 cm.

The only other factors which might affect the lifetime determination are errors in the measurement of the Λ^0 momentum and the Λ^0 decay length for individual events. These effects were studied in a Monte Carlo program by smearing the momentum and decay length of each event by our known momentum and length measurement errors. The lifetime changed by less than 0.01×10^{-10} sec as these quantities were smeared by several times our known errors. Systematic errors in the measurement of the momenta are less than a fraction of a percent, since the optical constants and the magnetic field in the chamber have been very carefully calibrated, using the monochromatic pions from a large sample of $K^-+p\to\Sigma^\pm+\pi^\mp$ events. This sensitivity of the lifetime to the momentum and the length errors, although quite negligible, has been folded into the error on the lifetime given above.

B. The Λ^0 Branching Ratio

The branching ratio R was calculated from the 4572 $\Lambda\to p\pi^-$ decays that passed the selection criteria of Sec. IIC, and a total of 10066 K^- stops which survived the quality checks and the range-curvature agreements described above.

A number of corrections have to be applied to these numbers to obtain the branching ratio:

(a) A weight, equal to the reciprocal of the detection probability, was calculated to correct for the losses due to the four selection criteria. The sum of the weights for the 4572 observed decays was 7167, or an average weight of 7167/4572 = 1.567. The error on this average weight, including the systematic uncertainty in the Λ lifetime and the measurement error on the Λ decay length, as evaluated by the Monte Carlo program, is ± 0.006. This error, combined with the statistical error on the number of Λ decays, gives an error of ±83 on the 7167 Λ decays. Note that the statistical error is not the square root of the number of events, but is given by binomial statistics.

(b) The scanning efficiency, not including systematic losses, is 99.9%, as discussed in Sec. IIE.

The correction for random scanning losses is thus 7 ± 7 events.

(c) A correction is necessary for the loss of vees with opening angle near 180°. This correction amounts to 94 ± 22 events, as discussed in Sec. II E. We apply the average weight appropriate for these events, since Fig. 7 is a distribution of unweighted events, to get $(94 \pm 22) \times 1.744 = 164 \pm 38$ events.

(d) The final correction to the number of $\Lambda \rightarrow p\pi^-$ decays is due to the fact that if the Λ scatters in the liquid hydrogen before its decay, the event will not make a kinematic fit to a $\Lambda \rightarrow p\pi^-$ decay with the Λ coming directly from the K^- stop. These events were part of the sample of vees which made poor or no kinematic fits that were examined by physicists. If a proton recoil from the Λ-p scatter was visible, or the Λ did not point to the K^- stop, the vee was discarded. The Λ-p scattering cross section and angular distribution are fairly well known[6,7] in this energy region. A Monte Carlo program was written, using this information, to calculate this correction to be 41 ± 9 events. The error is mostly due to the uncertainty in knowing exactly how many of the small-angle Λ scatters fit with good χ^2 as a Λ coming directly from the K^- stop.

(e) Whenever a $\Lambda \rightarrow p\pi^-$ decay occurs so close to the K^- stop that no gap is visible, the event looks like a two-prong K^- scatter, and both the vee and the K^- stop are discarded on the scanning table. If a vee has been measured, but is within 0.2 cm of the K^- stop (as projected on the film plane), both the vee and the K^- stop are discarded according to the selection criterion (b) of Sec. II C. (The other three selection criteria discard only vees, but retain the K^- stop.) A correction has to be therefore made to the total number of K^- stops for Λ decays within a projected 0.2 cm. The size of this correction was calculated using the sample of observed Λ decays. Each event was rotated by 90° around the beam direction, and the probability of that Λ, with its particular momentum and direction, decaying within a projected 0.2 cm of the K^- stop was computed. The net correction, which is this probability multiplied by the weight for each event [computed before rotating the events, as in (a) above], summed over all of the events in the sample, was 1497 ± 35 K^- stops to be added to the sample. The error of ± 35 is the systematic error only, due to the uncertainty in the Λ lifetime and the measurement error of the Λ-decay length. The statistical error on this correction is correlated with the total number of Λ decays, and was properly taken into account in calculating the error on the branching ratio.

(f) A very small fraction of the zero-prong events are in-flight K^-'s producing $\bar{K}^0$'s in the reaction $K^- p \rightarrow \bar{K}^0 n$. If the $\bar{K}^0$ decayed into $\pi^+\pi^-$, the vee was measured and identified as such in the kinematic fitting. There were 31 such events. The number of those events when the $\bar{K}^0$ does not decay in the chamber or decays into $\pi^0\pi^0$ must be subtracted from the total number of zero-prong events. This correction was calculated by weighting the 31 observed $\bar{K}^0 \rightarrow \pi^+\pi^-$ events for detection efficiency and using the ratio $(\bar{K}^0 \rightarrow \pi^+\pi^-)/(\bar{K}^0 \rightarrow \text{all})$, which is sufficiently well known for this purpose. The result was a correction of -135 ± 27 zero-prong events.

The branching ratio $R = (\Lambda \rightarrow p\pi^-)/(\Lambda \rightarrow \text{all})$ is thus

$$R = \frac{(7167 \pm 83) + (7 \pm 7) + (164 \pm 38) + (41 \pm 9)}{10066 + (1497 \pm 35) - (135 \pm 27)}$$

$$= 0.646 \pm 0.008.$$

The error on the final ratio was calculated taking the correlations between some of the corrections properly into account, and includes both statistical and systematic errors.

IV. CONCLUSIONS

The result obtained for the Λ mean life, $\tau = (2.54 \pm 0.04) \times 10^{-10}$ sec, is in good agreement with the average of previous measurements.[8]

The two previous measurements of the branching ratio R which had the smallest error were 0.643 ± 0.016,[2] and 0.685 ± 0.017,[3] not in very good agreement with each other. The result of this experiment, 0.646 ± 0.008, favors the first of these results.

The $\Delta I = \frac{1}{2}$ rule in Λ decay predicts a value $R = \frac{2}{3}$. This is modified to 0.659 when the phase-space correction due to the n-p and π^0-π^+ mass differences is taken into account. The radiative corrections to this branching ratio have been calculated by Belavin and Narodetsky.[1] Their result raises the branching ratio to 0.674, including the phase-space correction. Without the radiative corrections, our result is not in serious disagreement with the $\Delta I = \frac{1}{2}$ rule. With the radiative corrections, however, the disagreement approaches $3\frac{1}{2}$ standard deviations. There are, however, some uncertainties in the radiative corrections, and it is not clear how seriously this disagreement with the $\Delta I = \frac{1}{2}$ rule should be taken.

ACKNOWLEDGMENTS

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†Present address: University of California, Berkeley, California.

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π^+p Elastic Scattering Data between 1820- and 2090-MeV c.m. Energy*

G. E. Kalmus, W. Michael, and R. W. Birge

Lawrence Radiation Laboratory, University of California, Berkeley, California 94720

and

S. Y. Fung and A. Kernan

University of California, Riverside, California 92502

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Total and differential elastic cross-section data are presented at eight incident π^+ momenta: 1.28, 1.34, 1.40, 1.43, 1.55, 1.68, 1.77, and 1.84 GeV/c. These data were obtained from a hydrogen-bubble-chamber exposure at the Bevatron, and contain more than 65 000 events. This represents more than $1\frac{1}{2}$ times the world's data hitherto available in this energy region.

I. INTRODUCTION

We present total and differential cross sections for π^+p elastic scattering at eight incident π^+ momenta: 1.28, 1.34, 1.40, 1.43, 1.55, 1.68, 1.77, and 1.84 GeV/c. These data, byproducts of an extensive investigation of inelastic π^+p scattering, represent more than 1.5 times the world's differential cross-section data, up to now, in this energy region.[1-6] They result from the measurement of about 230 000 "two-prong" interactions in the Lawrence Radiation Laboratory 72- and 25-in. bubble chambers. The range in the cosine of the production angle covered by the data is $-1.0<\cos\theta^* <0.98$ at the six higher momenta, and $-1.0<\cos\theta^* <0.96$ at the two lower momenta, where θ^* is the angle in the c.m. system between the pion in the final state and the beam direction.

II. EXPERIMENTAL PROCEDURE

A. Beam

The π^+ beam used for the three momenta in the 72-in. chamber (1.34, 1.43, and 1.68 GeV/c) had a single stage of separation with two vertical slits, the second being used to clean up the beam close to the bubble chamber. The momentum bite of the beam was $<\pm 1\%$. The proton contamination of the