Lifetimes of the Ξ^- and Ξ^0 Hyperons*

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(Received 7 February 1964)

A sample of 794 Ξ^- hyperons and 101 Ξ^0 hyperons has been used in a determination of the Ξ^- and Ξ^0 lifetimes. We find $\tau_{\Xi^-}=1.69\pm0.07\times10^{-10}$ sec and $\tau_{\Xi^0}=2.5_{-0.3}^{+0.4}\times10^{-10}$ sec. The ratio of the Ξ^0 decay rate to the Ξ^- decay rate, $\lambda_{\Xi^0}/\lambda_{\Xi^-}=0.68\pm0.10$, is within two standard deviations of the $|\Delta T|=\frac{1}{2}$ prediction of 0.5.

INTRODUCTION

WE report here a determination of the lifetimes of the Ξ^- and Ξ^0 hyperons with greater statistical accuracy than previously reported.[1–11] Our result is not in disagreement with earlier determinations. The ratio of the Ξ^0 decay rate to the Ξ^- decay rate, $\lambda_{\Xi^0}/\lambda_{\Xi^-}=0.68\pm0.10$, is within two standard deviations of the $|\Delta T|=\frac{1}{2}$ prediction of 0.5.[12]

Nine hundred Ξ^- hyperons and about 200 Ξ^0 hyperons were observed in an experiment that exposed the 72-in. bubble chamber to K^- mesons. The incident momentum was varied in 100-MeV/c steps from 1.0 to 1.7 BeV/c. Half of these data were obtained at 1.5 BeV/c.

The Ξ^- were distributed among the reactions

$$K^-+p\rightarrow\Xi^-+K^+,\quad 828\text{ events};\quad(1)$$

$$K^-+p\rightarrow\Xi^-+K^0+\pi^+,\quad 53\text{ events};\quad(2)$$

and

$$K^-+p\rightarrow\Xi^-+K^++\pi^0,\quad 19\text{ events}.\quad(3)$$

The Ξ^0 were obtained from the reactions

$$K^-+p\rightarrow\Xi^0+K^0,\quad(4)$$

$$K^-+p\rightarrow\Xi^0+K^0+\pi^0,\quad(5)$$

and

$$K^-+p\rightarrow\Xi^0+K^++\pi^-.^{13}\quad(6)$$

The Ξ then decays, producing a Λ. Only events in which the Λ from the Ξ decay is observed to decay into two charged particles were included in our sample. All except two decays were compatible with the mode $\Lambda\rightarrow p+\pi^-$; two of the Λ's were definite β decays, i.e., $\Lambda\rightarrow p+e^-+\bar{\nu}_e$. The problems of determining the Ξ^- and Ξ^0 lifetimes are sufficiently different that we choose to discuss them separately.

Ξ^- LIFETIME

Topologically, each Ξ^- candidate is identified as a two-prong with a decay kink on the negative track and an associated "vee." (See Fig. 1.) In reaction (2), there may be a second associated "vee".

We have attempted to minimize the systematic errors due to scanning bias by imposing acceptance criteria; we require both the Ξ^- and Λ to travel at least 0.5 cm in the chamber. We have further insisted that both hyperon decay points lie within a fiducial volume to ensure measurability of the events. These restrictions reduce the sample to 794 events. The film has been scanned twice to ensure that there is no dependence of scanning efficiency on Ξ^- decay length.

To determine the observed decay lives for each event we need the momentum, path length, and mass for the Ξ^- and Λ. The momenta were determined by constraining each event as a whole, including the Ξ^- production, Ξ^- decay, and Λ decay vertices to satisfy energy-momentum conservation. Typically the hyperon momenta are determined to better than 1%. Of the 794 events accepted for the lifetime analysis, only one event yields ambiguous interpretations for the production process. The systematic error in the hyperon momenta due to such misidentification is thus negligible. Each vertex is well defined by at least two charged tracks; consequently, the average precision of our hyperon length measurements is about 1%. The mass

* Work done under the auspices of the U. S. Atomic Energy Commission.

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[13] Roughly 50 $\Xi^0K^+\pi^-$ events have been observed. These events have not yet been fully analyzed. They were excluded from this lifetime determination.

used for the Ξ^- was 1321 MeV. The distribution of proper times of flight for our sample is given in Fig. 2.

The probability, for the kth event, of observing proper times t_{1k} and t_{2k} for the Ξ^- and Λ with decay rates $\lambda_1 = \tau_{\Xi^-}^{-1}$ and $\lambda_2 = \tau_\Lambda^{-1}$ is

$$P_k(t_{1k},t_{2k};\lambda_1,\lambda_2) = f_k(\lambda_1,\lambda_2)\lambda_1\lambda_2 \exp(-\lambda_1 t_{1k} - \lambda_2 t_{2k}),$$

where $f_k(\lambda_1,\lambda_2)$ normalizes the probability to unity.

$$\frac{1}{f_k(\lambda_1,\lambda_2)} = \int_{a_{1k}}^{b_{1k}} dt_1 \int_{a_{2k}(t_1)}^{b_{2k}(t_1)} dt_2 \lambda_1\lambda_2 \exp(-\lambda_1 t_1 - \lambda_2 t_{2k}),$$

where the allowable t_2 depend on t_1.

The log of the likelihood function is then

$$w(\lambda_1,\lambda_2) = \ln\mathcal{L}(\lambda_1,\lambda_2) = \sum_{k=1}^{N} \ln P_k(t_{1k},t_{2k};\lambda_1,\lambda_2)$$

$$= (N\ln\lambda_1 - \lambda_1 T_1) + (N\ln\lambda_2 - \lambda_2 T_2)$$

$$-\sum_{k=1}^{N} \ln\left\{\int_{a_{1k}}^{b_{1k}} dt_1 \int_{a_{2k}}^{b_{2k}(t_1)} dt_2 \lambda_1\lambda_2 \exp(-\lambda_1 t_1 - \lambda_2 t_{2k})\right\}.$$

Here $T_1 = \sum_{k=1}^{N} t_{1k}$ and $T_2 = \sum_{k=1}^{N} t_{2k}$ are the total proper times of flight for the Ξ^- and Λ, respectively; $a_{1k} = (MA_1/cp_k)_\Xi$, $a_{2k} = (MA_2/cp_k)_\Lambda$, $b_{1k} = (ML_{1k}/cp_k)_\Xi$, $b_{2k} = (ML_{2k}/cp_k)_\Lambda$; A_1 and A_2 are the minimum observed length cutoffs for the Ξ^- and Λ, respectively. L_{1k} is the maximum possible Ξ^- length for this event, and $L_{2k}(x_1)$ is the maximum possible length for the Λ of this event if it originates from the position $x_1 = (p_k c t_1/M)_\Xi$ along the Ξ^- path.

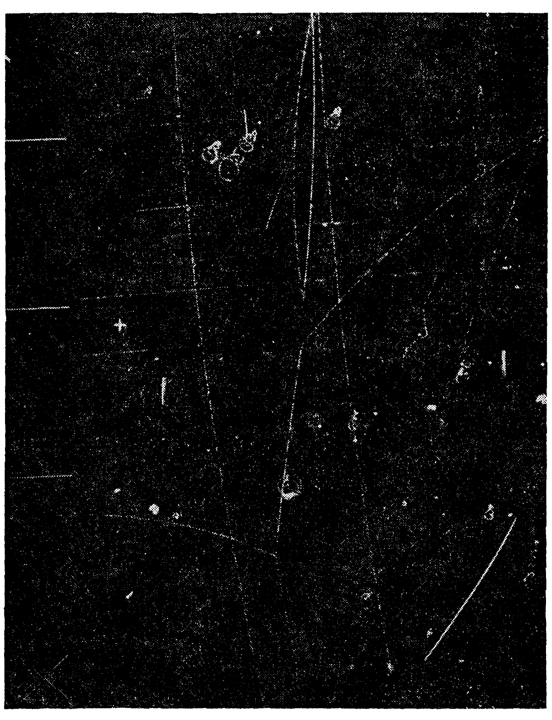

FIG. 1. Production and decay of a Ξ^-.

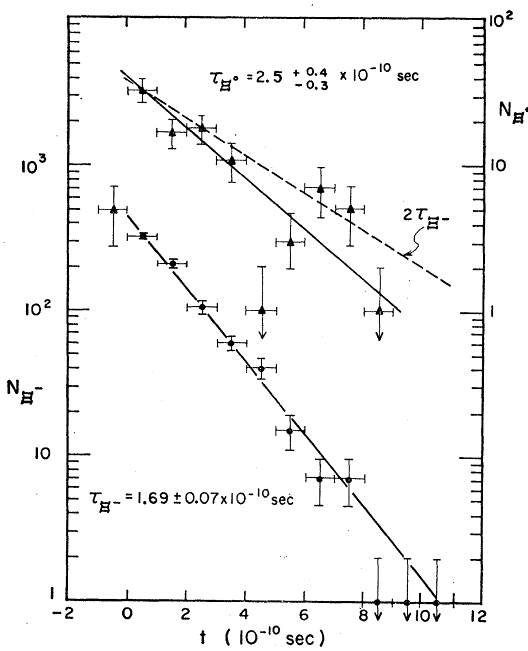

FIG. 2. Lifetime distributions of Ξ^- and Ξ^0. The Ξ^0 data are represented by triangles, with the scale on the right; the proper times of the Ξ^- beyond the minimum length cutoff are represented by circles, with the scale on the left. The number of events shown is not corrected for detection efficiency; since the bubble chamber is very large compared with the mean decay distance of the Ξ, the uncorrected data fit the decay curve well. The slope of the upper solid line is $\tau_{\Xi^0}^{-1} = 1/(2.5\times10^{-10}$ sec); the slope of the lower solid line is $\tau_{\Xi^-}^{-1} = 1/(1.69\times10^{-10}$ sec). These correspond to the best-fit values for τ_{Ξ^0} and τ_{Ξ^-} from likelihood functions. The slope of the broken line is $(2\tau_{\Xi^-})^{-1} = 1/(3.38\times10^{-10}$ sec), corresponding to the $|\Delta T| = \frac{1}{2}$ prediction for the Ξ^0 data. The two lines through the Ξ^0 data have been arbitrarily normalized to the $t = 0.5\times10^{-10}$-sec point; the line through the Ξ^- data has been arbitrarily normalized to the $t = 2.5\times10^{-10}$-sec point. Note that the calculated proper times of five Ξ^0's were negative (Ref. 18).

The likelihood function was maximized as a function of λ_1 and λ_2 simultaneously.[14] We obtain

$$\tau_{\Xi^-} = 1.69 \pm 0.06 \times 10^{-10}\ \text{sec},^{15}$$

$$\tau_\Lambda = 2.59 \pm 0.09 \times 10^{-10}\ \text{sec}.$$

Variation of τ_Λ between 2.45×10^{-10} and 2.75×10^{-10} sec produces a shift in τ_{Ξ^-} of less than 0.01×10^{-10} sec. This shift is small, since the Ξ and Λ lifetimes are correlated only through the correction for the finite size of the bubble chamber. Variation of the various cutoff criteria produces a shift in τ_{Ξ^-} of less than 0.02×10^{-10} sec.

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[14] Because of the existing discrepancies in published values of τ_Λ, we have made an independent measurement. For a recent compilation see F. S. Crawford, Jr., in *Proceedings of the International Conference on High Energy Physics* (CERN, Geneva, 1962).

[15] The stated errors, both for τ_{Ξ^-} and τ_{Ξ^0}, refer to the shift in lifetime necessary to decrease the log of the likelihood by 0.5.

When the various systematic uncertainties are included with the statistical uncertainty we obtain our final result, $\tau_{\Xi^-}=1.69\pm0.07\times10^{-10}$ sec.

Ξ^0 LIFETIME

Topologically any zero-prong with two associated "vees" is a candidate for Ξ^0K^0 production. (See Fig. 3.) This topology includes π^- interactions such as ΛK^0 production. The π^- contamination of the K^- beam was about 2% at 1.5 BeV/c and up to 10% at the other momenta. The rather large spread in the momenta of the contaminating π^- results in more frequent ambiguous interpretations when the incident momentum is not measured accurately. To minimize this effect only those events produced by a beam track longer than 25 cm have been included in our sample. The measurement uncertainty in the incident momentum is thus less than 3%. Furthermore, because of the high-π^- contamination at the lower momenta, the data with beam momentum below 1.3 BeV/c were not included.

In general the π^0 from the decay of a Ξ^0 is not observed. Therefore, an event is kinematically constrained only if the Λ decays in the two-body charged mode ($\Lambda\rightarrow p+\pi^-$). Only those events in which the Λ and the K^0 were both observed to decay via their two-body charged modes were retained. The K^0 was required to come directly from the production vertex without scattering.

The sample of 139 events satisfying the above requirements was separated into two categories. The first

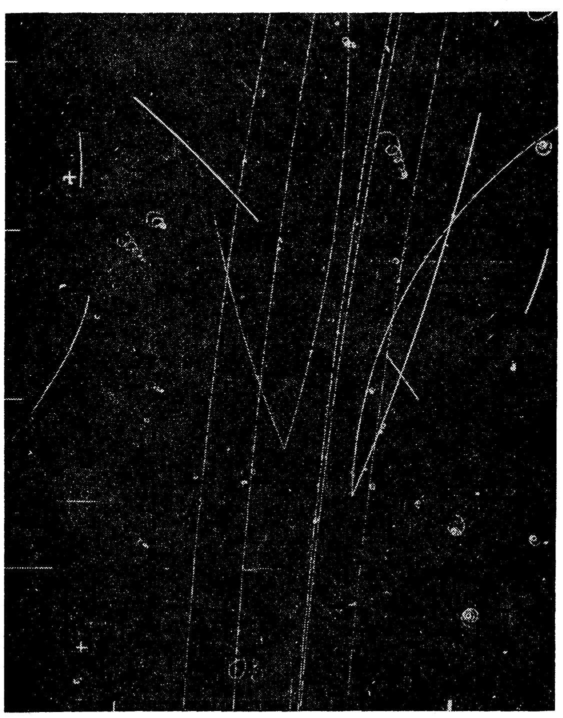

FIG. 3. Production and decay of a Ξ^0.

consisted of 61 events for which the fitted Λ's were not consistent with coming directly from the production vertex. Of these 61 events, 57 were unambiguous $K^-+p\rightarrow\Xi^0+K^0$ events. The remaining four events were consistent with $K^-+p\rightarrow\Xi^0+K^0+\pi^0$, and were eliminated from our sample. The second category of $(139-61)=78$ events, in which the fitted Λ's were consistent with coming directly from the production vertex, was then fitted to the following hypotheses:

$$\begin{array}{lll}\text{(a)} & K^-+p\rightarrow\Xi^0+K^0\,, & \text{3 constraints;}\\ \text{(b)} & \pi^-+p\rightarrow\Lambda+K^0\,, & \text{4 constraints;}\\ \text{(c)} & \pi^-+p\rightarrow\Sigma^0+K^0\,, & \text{2 constraints;}\end{array}$$

and

$$\text{(d)}\ \pi^-+p\rightarrow\Lambda+K^0+\pi^0\,,\quad \text{1 constraint.}$$

Of the 78 events of this second category, 66 were identified unambiguously as follows: 37 Ξ^0K^0 events (a), 20 ΛK^0 events (b), five Σ^0K^0 events (c), and four $\Lambda K^0\pi^0$ events (d). Two additional events were consistent with $\Xi^0K^0\pi^0$ production, and were removed from the sample. The remaining 10 events fitted both Ξ^0K^0 (a) and Σ^0K^0 (c); seven of these gave better fits for Ξ^0K^0 production and were included in our sample.[16] Thus, $(57+37+7)=101$ events were included in our sample.

The distance from the Λ decay vertex to the Ξ^0 production vertex is very nearly the sum of the Ξ^0 decay length plus the Λ decay length. The reason for this is that the Λ direction differs by less than 20 deg from that of the Ξ^0 at our momenta. Events with Λ's that decay too close to the production vertex can be misidentified in the scanning process. Consequently, we required that the Λ decay at least 0.5 cm from the production vertex. No Ξ^0 events in our sample were eliminated by this restriction; *a posteriori* we would have expected only $\frac{1}{4}$ event to fail this criterion.

Events could also have been missed because the Λ decays so far from the production vertex that our scanners might fail to associate it with the proper production vertex. By comparing the events found within the visible volume of the chamber on the first scan with those found on the second scan we find that the scanning efficiency is 99%, independent of the distance of the Λ decay from the production vertex.

The complete analysis of the reaction chain

$$\begin{array}{cccc} K^-+p\rightarrow & \Xi^0 & + & K^0\\ & \downarrow & & \downarrow\\ & \Lambda+\pi^0 & & \pi^++\pi^-\\ & \downarrow & & \\ & p+\pi^- & & \end{array}$$

proceeded as follows: First the Λ and K^0 decays were fitted kinematically; for the K^0 there are three constraints, for the Λ only one, since the line of flight of the Λ is unknown. An over-all fit to the Ξ^0 production and decay was then performed, using the Λ and K^0 momen-

[16] The uncertainty in our final result includes the possible shift in τ_{Ξ^0} resulting from the uncertainty in our sample.

tum vectors obtained from the Λ and K^0 decay fits. This over-all fit is subject to two kinematic constraints: there are eight equations of energy and momentum balance and six unknowns, the momentum vectors of the Ξ^0 and the π^0. In addition, there is a geometrical constraint: The line of flight of the Λ must intersect that of the Ξ^0 in space.[17]

The Ξ^0 and Λ momenta obtained in the fit have uncertainties of the order of 5%. The flight distance of the Ξ^0 and its uncertainty were calculated by using the length of the link from the Ξ^0 production to the Λ decay vertex and the Ξ^0 and Λ direction and errors obtained from the fit.[18] The uncertainty in the calculated Ξ^0 flight distance is typically 20%.

There are six events in the sample for which the decay point may be measured independent of the kinematic fit. In four of these events the π^0 from the Ξ^0 decays into a γ ray plus a Dalitz pair ($e^\pm$). In two events γ-ray conversions associated with the π^0 from the Ξ^0 decays were observed near the Ξ^0 decay points. The decay points of these six events were also determined by the method used for the other events. The calculated lengths averaged 15% (two standard deviations) higher than the measured lengths. The mass used for the Ξ^0 was 1315 MeV. The distribution of proper times of flight for our sample is given in Fig. 2.

The uncertainty in the individual proper times is appreciable, so we fold a Gaussian error function Q into our probability function

$$P'_k(l_{1k},l_{3k};\lambda_1,\lambda_2)=\int_0^{l_{3k}} dxQ(x,l_{1k})P_k(t_1(x),t_2(x);\lambda_1,\lambda_2)\,,$$

where

$$Q(x,l)=\frac{1}{\sqrt{2}\pi^{1/2}\sigma_k}\exp[-(x-l)^2/2\sigma_k^2]$$

and

$$P_k(t_1,t_2;\lambda_1,\lambda_2)=f_k(\lambda_1,\lambda_2)\lambda_1\lambda_2\exp(-\lambda_1 t_1-\lambda_2 t_2)\,,$$

as before. The $t_1(x)$ and $t_2(x)$ are the proper times for the Ξ^0 and Λ, obtained by holding l_{3k} constant and assuming that the true position of the Ξ^0 decay was at a distance x from the Ξ^0 production vertex; l_{3k} is the measured length of the link from the production vertex to the Λ decay point; and l_{1k} and σ_k are the calculated Ξ^0 length and its uncertainty. We obtain for the log of the likelihood function

$$w(\lambda_1,\lambda_2)=\ln\mathcal{L}(\lambda_1,\lambda_2)=\sum_{k=1}^{N}\ln P'_k(l_{1k},l_{3k};\lambda_1,\lambda_2)$$
$$=(N\ln\lambda_1-\lambda_1T_1)+(N\ln\lambda_2-\lambda_2T_2)$$
$$-\sum_{k=1}^{N}\ln\left\{\int_0^{b_{1k}}dt_1\int_{a_{2k}(t_1)}^{b_{2k}(t_1)}dt_2\lambda_1\lambda_2\exp(-\lambda_1t_1-\lambda_2t_2)\right\}$$
$$+\sum_{k=1}^{N}\ln\left\{\frac{1}{\sqrt{2}\pi^{1/2}\sigma_k}\int_0^{l_{3k}}dx\right.$$
$$\left.\times\exp\left[-\frac{1}{2}\frac{(x-l_{1k})^2}{\sigma_k^2}-\lambda_1(t_1(x)-t_{1k})-\lambda_2(t_2(x)-t_{2k})\right]\right\}.$$

This likelihood function was maximized as a function of the Ξ^0 lifetime only. We obtain $\tau_{\Xi^0}=2.50_{-0.26}^{+0.33}\times10^{-10}$ sec. This result is rather insensitive to the Λ lifetime assumed. We used $\tau_\Lambda=2.59\times10^{-10}$ sec, the value obtained from the Ξ^- events; variation of τ_Λ from 2.45×10^{-10} to 2.75×10^{-10} sec produces a shift in τ_{Ξ^0} of less than 0.01×10^{-10} sec. As a consistency check we used the calculated proper times of flight of the Λ's to determine the Λ lifetime. We find $\tau_\Lambda=2.89_{-0.30}^{+0.37}\times10^{-10}$ sec, which is consistent with other measured values.[14]

As previously mentioned, 7 of the 10 events that fitted both $K^-+p\rightarrow\Xi^0+K^0$ and $\pi^-+p\rightarrow\Sigma^0+K^0$ were included in our sample. The sample has been varied to determine the effect of these ambiguous interpretations on our result; τ_{Ξ^0} varies from 2.42×10^{-10} to 2.61×10^{-10} sec when these 10 ambiguous events are all included or all excluded, respectively.

TABLE I. Ξ^- lifetime.

Experiment and reference	N_{Ξ^-}	τ_{Ξ^-} ($\times10^{-10}$ sec)	λ_{Ξ^-} ($\times10^{10}$ sec^{-1})
Trilling and Neugebauer (Ref. 1)	7	>1.8	...
Fowler *et al.* (Ref. 2)	2	1–10	...
Fowler *et al.* (Ref. 4)	18	$1.28_{-0.25}^{+0.41}$	0.78 ±0.19
Wang Kang-Ch'ang *et al.* Ref. 5	11	$3.5_{-1.2}^{+3.4}$	0.29 ±0.14
Bertanza *et al.* (Ref. 6) / Connolly *et al.* (Ref. 11)	273	$1.74_{-0.15}^{+0.18}$	0.575±0.054
Jauneau *et al.* (Refs. 7, 9)	320	$1.91_{-0.15}^{+0.17}$	0.524±0.044
Schneider (Ref. 8)	62	1.55±0.31	0.65 ±0.13
Carmony *et al.* (Ref. 10)	356	1.77±0.12	0.565±0.038
This experiment	794	1.69±0.07	0.592±0.025

TABLE II. Ξ^0 lifetime.

Experiment and reference	N_{Ξ^0}	τ_{Ξ^0} ($\times10^{-10}$ sec)	λ_{Ξ^0} ($\times10^{10}$ sec^{-1})
Alvarez *et al.* (Ref. 3)	1	≈1.5	...
Jauneau *et al.* (Ref. 7)	16	$3.9_{-0.8}^{+1.4}$	0.26±0.07
Caromony *et al.* (Ref. 10)	54	$3.5_{-0.8}^{+1.0}$	0.29±0.07
This experiment	101	$2.5_{-0.3}^{+0.4}$	0.40±0.06

[17] This condition is equivalent to the requirement that the Ξ^0 momentum vector, the Λ momentum vector, and the vector linking the point of interaction of the K^- with the point of decay of the Λ be coplanar. It was this requirement that was incorporated into our computer program; see B. Pardoe, Alvarez Physics Note 398, Lawrence Radiation Laboratory, 1962 (unpublished).

[18] The flight distance so calculated is not necessarily positive, since the calculated Λ line of flight may intersect the Ξ^0 line of flight before rather than after the point of production; this causes no difficulty if the errors are properly included in the subsequent analysis.

Variation of our cutoff criteria for events in which the Λ decays too near to or too far from the Ξ^0 production vertex produces a shift in τ_{Ξ^0} of less than 0.15 $\times 10^{-10}$ sec.

When these systematic uncertainties are included with the statistical and measurement uncertainties, we obtain our final result:

$$\tau_{\Xi^0}=2.5_{-0.3}^{+0.4}\times 10^{-10}\text{ sec}.$$

DISCUSSION OF RESULTS

The determinations of the Ξ^- and Ξ^0 lifetimes reported to date are summarized with our results in Tables I and II.[19] It is seen that there are no statistically significant discrepancies among these results.

The ratio of the Ξ^0 decay rate to the Ξ^- decay rate provides a sensitive test to the rule $|\Delta T|=\frac{1}{2}$ rule for nonleptonic, strangeness-changing weak decays.[12] Our result, $\lambda_{\Xi^0}/\lambda_{\Xi^-}=0.68\pm0.10$, is within two standard deviations of the $|\Delta T|=\frac{1}{2}$ prediction of 0.5.

ACKNOWLEDGMENTS

We wish to thank Professor Harold K. Ticho and Professor Donald H. Stork for participation in the design and construction of the separated K^- beam. We are especially grateful to Margaret Alston for her work on many aspects of the analysis of this experiment. We wish to express appreciation to Robert Watt and the crew of the 72-in. bubble chamber and to Jacob Neufeld and the scanning and measuring personnel. The support and encouragement of Professor Luis W. Alvarez is gratefully acknowledged.

[19] The weighted averages of the Ξ^- and Ξ^0 lifetimes quoted in Tables I and II are $\tau_{\Xi^-}=1.75\pm0.05\times10^{-10}$ sec and $\tau_{\Xi^0}=3.1_{-0.3}^{+0.4}\times10^{-10}$ sec. The resulting ratio of decay rates, $\lambda_{\Xi^0}/\lambda_{\Xi^-}=0.57\pm0.07$, is within one standard deviation of the $|\Delta T|=\frac{1}{2}$ prediction. Because of the different methods used in the lifetime analyses by the various groups, such "world averages," although interesting, may not be significant.

PHYSICAL REVIEW VOLUME 135, NUMBER 1B 13 JULY 1964

Weak Corrections to the Magnetic Moments of Leptons*

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(Received 14 February 1964)

A calculation of the contribution of the weak interactions to the magnetic moments of the leptons is reported. An intermediate vector boson is assumed, and lowest order effects are calculated. The radiative corrections to these results are estimated by making use of the summation technique introduced by Lee. The contributions are small compared to the uncertainties in the experimental values of the magnetic moments. For the muon the changes in the magnetic moment are at least an order of magnitude smaller than the contributions of the strong interactions. If the muon's neutrino has a relatively large mass, its induced magnetic moment will affect the neutrino scattering cross sections calculated by Bernstein and Lee.

I. INTRODUCTION

THE electromagnetic properties of the leptons (and the intermediate vector boson W) are of particular interest: For all of the other particles the significance of at least some of these properties is complicated by the presence of strong interactions. The values of the charge and the magnetic moment of the electron and the associated errors have been given by Du Mond.[1] The corresponding quantities for the muon have been given by Shapiro and Lederman.[2] Recently, Bernstein, Ruderman, and Feinberg[3] have indicated the uncertainties in the experimental values of the charges, magnetic moments, and charge radii of the neutrinos.

In this paper we calculate the contributions of the weak interactions to the magnetic moments of the leptons. We assume that the weak interactions are mediated by a vector boson. The lowest order contributions to the moments of the charged leptons are calculated in Sec. II. In Sec. III a similar analysis is carried out for the neutrinos. Section IV consists of an an estimate of the effect of higher order electromagnetic and weak interactions upon the leptonic magnetic moments. The conclusions follow in Sec. V.

II. CHARGED LEPTONS

We note, to begin with, that the electromagnetic properties of the W particle have been the subject of some discussion.[4] The suggestion is that the assumption

* Supported by the U. S. National Science Foundation.
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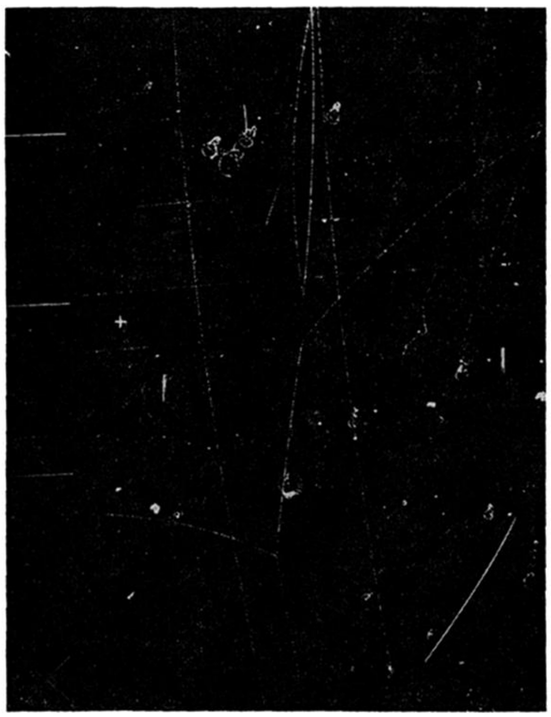

FIG. 1. Production and decay of a Ξ^-.

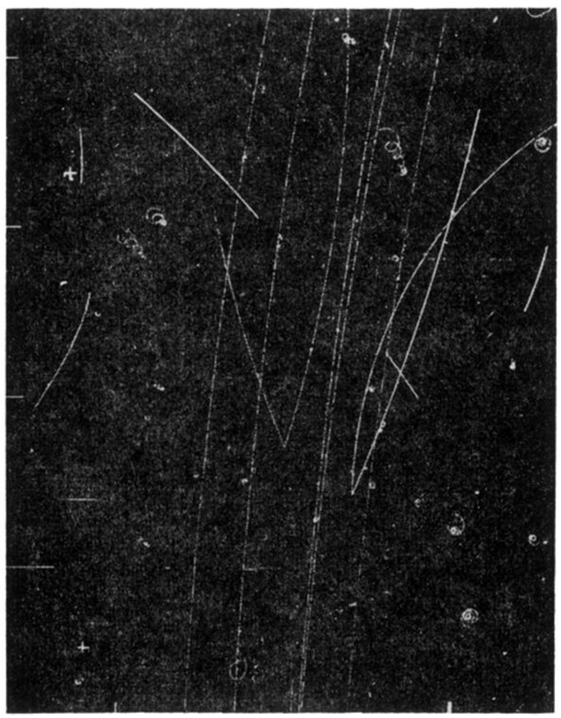

FIG. 3. Production and decay of a Ξ^0.