collimated and the background is appreciable. The method will not be useful at lower energies, since polarization in the scattering by most nuclei falls off sharply at lower energies.[4] It will be useful for higher proton energies, however, since polarized protons can be slowed down to 150 Mev without appreciable depolarization.[5]

Furthermore, the technique can be applied to other elements by comparing the track distribution, as observed in the emulsion, with and without some scattering material interposed in the beam.

(b) Evidence on the nuclear spin-orbit potential. The curves in Figs. 1 and 2 were computed by Sternheimer[6] for $Z=41$, corresponding to the average Z for Ag and Br. These curves indicate the possibility of obtaining additional useful information concerning the nature of the nuclear spin-orbit potential. Indeed, if we consider the region below 14°, our experimental points speak somewhat in favor of the curves calculated with finite imaginary spin-orbit potential.[7] However, since, as pointed out by Bethe,[8] it is $|u|$ which is responsible for the shape and magnitude of polarization, it will be necessary to establish the value of the real part before any definite conclusions can be drawn concerning the magnitude of the imaginary spin-orbit potential.

(c) Polarization in small-angle scattering. In our first observations, previously reported,[9] scatterings were observed by following each proton track. Since each track had, on the average, only a 4% probability of exhibiting a scattering before leaving the emulsion, the extraction of a statistically significant result required lengthy and laborious scanning. These results, shown as triangles in Fig. 2, show a negative polarization $-(0.16\pm0.10)$ in the angular region of Coulomb scattering, around 2°.

A negative polarization at small angles is to be expected,[8,10] as a result of interference between the (repulsive) Coulomb scattering and the nuclear spin-orbit interaction. Relatively crude arguments would indicate a fairly large effect,[11] although the more refined computations of Sternheimer[6] reduce the expected effect below the experimental indications. Since our first report on the small-angle polarization,[9] the Uppsala group[12] has reported $P=-(0.067\pm0.02)$ at 2° in oxygen at the same energy.[13] Although the large uncertainty makes it difficult to be sure of the magnitude, we have additional indications that our observations in the "Coulomb region" may represent a real effect. This evidence comes from observations of asymmetries which develop in the angular distribution of the beam in passing through the emulsion, as well as from multiple-scattering measurements on individual tracks. The interpretation of such observations is complicated by the difficulty of distinguishing between multiple and single (or plural) scattering effects in the angular region of interest. Work is in progress towards the development of methods of observation and interpretation appropriate to this angular range.

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*Work supported in part by joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

[1] E. L. Grigor'ev, J. Exptl. Theoret. Phys. (U.S.S.R.) 28, 761 (1955).

[2] J. Friedman, Phys. Rev. 104, 794 (1956).

[3] We are indebted to Professor K. Strauch and R. Wilson for their cooperation.

[4] L. Wolfenstein, Annual Review of Nuclear Science, (Annual Reviews, Inc., Stanford, 1956), Vol. 6, p. 43.

[5] L. Wolfenstein, Phys. Rev. 75, 1665 (1949).

[6] R. M. Sternheimer, Phys. Rev. (to be published).

[7] W. Heckrotte, Phys. Rev. 101, 1406 (1956).

[8] H. A. Bethe, Ann. Phys. 3, 190 (1958).

[9] B. C. Maglić and B. T. Feld, Padua-Venice Conference on Mesons and Recently Discovered Particles (Italian Physical Society, Bologna, 1957), p. XVI-1.

[10] To our knowledge, the first suggestion came from J. Cassels, Proceedings of the Fifth Annual Rochester Conference on High-Energy Physics, 1955 (Interscience Publishers, Inc., New York, 1955), p. 158.

[11] I. e., Born approximation computations of the type first suggested by E. Fermi, Nuovo cimento 11, 407 (1954).

[12] Alphonce, Johansson, and Tibell, Nuclear Phys. 4, 672 (1957).

[13] J. Friedman (private communication) also finds indications, on closer examination of his published data,[2] of such an effect.

BETA DECAY OF THE Λ†

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In the course of studying a large number of decays of hyperons, produced in our hydrogen bubble chamber by 1.23-Bev/c pions, we have found an unambiguous case of a Λ undergoing

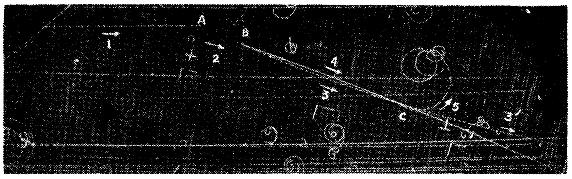

Fig. 1. Photograph of the event. The distance from vertex B to vertex C is 5 cm.

beta decay. To our knowledge this is the first leptonic Λ decay seen.[1]

Figure 1 is a photograph of the event. All of the tracks except track 5 lie nearly in the plane of the photograph. We believe that the sequence of events occurring at the vertices labeled, A, B, and C is as follows (the track numbers appear in parentheses):

$$\pi^-(1) + p - (A) \rightarrow K^0 + \Sigma^0, \quad \Sigma^0 \rightarrow \gamma + \Lambda(2),$$

$$\Lambda(2) - (B) \rightarrow p(4) + e^-(3) + \bar{\nu},$$

$$e^-(3) + e^- - (C) \rightarrow e^-(3') + e^-(5).$$

Table I summarizes the measured quantities for tracks associated with vertices A and B. Table II does the same for vertex C.

The event was first noticed to be anomalous when the neutral decay $2 \rightarrow 3 + 4$ at vertex B failed to fit the normal two-body decay of either a K_1^0 or a Λ. In particular, tracks 3 and 4 both lie on the "left" side of the extension of track 2, and momentum conservation requires an unobserved neutral carrying 34.6 ± 8.2 Mev/c momentum transverse to the "right," and 55 ± 42 Mev/c into the plane of the photograph, with respect to track 2.[2]

Ionization measurements convince us that track 4 is a proton, as follows: Figure 2 shows a semilogarithmic plot of the distribution of gap lengths between successive bubbles, for tracks 3 and 4. The ratio of slopes in the unsaturated (straight-line) region, where the gap size exceeds the average bubble diameter, is 2.65 ± 0.32. This should correspond to the ratio of (unsaturated) average number of bubbles per unit track length.[3] The predicted ionization ratios are as follows: $I_4(\pi^+)/I_3(\pi^- \text{ or } e^-) = 0.87 \pm 0.04$,[4] $I_4(\text{proton})/I_3(\pi^- \text{ or } e^-) = 3.4 \pm 0.6$. It is clear that track 4 can only be a proton. We emphasize that tracks 3 and 4 pass through almost exactly the same region of liquid hydrogen, at the same time, so that any possible spatial or temporal variation in chamber sensitivity is irrelevant.

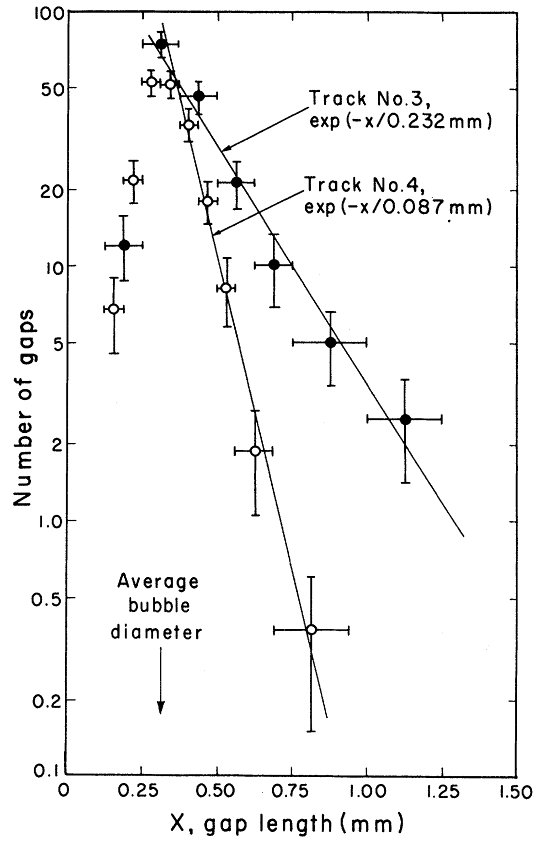

Fig. 2. Distributions of gap lengths between successive bubbles for tracks 3 and 4.

Analysis of vertex C rules out the possibility that track 3 is a pion, and gives roughly 30 to 1 odds in favor of its being an electron rather than a muon, as follows: Track 5 is an electron which eventually goes into the top glass. Its minimum momentum, based only on its visible range, is 3.65 ± 0.1 Mev/c. Curvature measurements give 3.8 ± 0.8 Mev/c. Microscope measurements show that track 3 suffers a deflection at C. Track 5 extrapolates accurately to the point of deflection and is therefore not an accidentally associated electron. If track 3 were a 210-Mev/c pion, the

Table I. Measured momentum, azimuth, and dip for tracks associated with vertices A and B.

Track	Momentum (Mev/c)	Azimuth, ϕ (degrees)	Dip, λ (degrees)
1	1230 ± 20	103.3 ± 0.3	-0.03 ± 1.6
2	...	80.4 ± 0.4	8.9 ± 4.9
3	210 ± 20	$80.4 + (0.54 \pm 0.3)$	2.5 ± 1.4
4	424 ± 50	$80.4 + (4.9 \pm 1)$	4.6 ± 0.8

Table II. Measured momentum, azimuth, and dip for tracks associated with vertex C, along with best-fit values for the hypothesis that $3 \rightarrow 3' + 5$ is an elastic electron-electron collision.

Track	Mpmentum (Mev/c)	Azimuth, $\phi - \phi_3$ (degrees)	Dip, $\lambda - \lambda_3$ (degrees)
3, measured	210 ± 20	0	0
3, best fit	210	0	0
3′, measured	205 ± 15	$+1.6 \pm 0.4$	-3.8 ± 2.0
3′, best fit	207	$+0.42$	$+0.40$
5, measured	$3.8_{-0.2}^{+0.8}$	-19.4 ± 2.8	-18.9 ± 7.3
5, best fit	3.8	-23.0	-21.0

maximum momentum it could give a delta-ray electron would be 2.8 Mev/c, so that the energy alone of track 5 rules out a pion. If one stretches all of the measured quantities so as to minimize chi square, one obtains a chi square of 44, where the "expected" value is 4. If track 3 is either a muon or an electron it can furnish the necessary energy to track 5 as a delta ray, but in both cases there is some difficulty in providing the large transverse momentum of 5.9 ± 1.5 Mev/c imparted to track 3′. The hypothesis that track 3 is an electron giving a delta ray at C yields a chi square of 11 where 4 is "expected," and corresponds to a probability of 0.030 for a fit this bad or worse. If instead track 3 is a muon, the fit is much worse, yielding a chi square minimum of 20 and a corresponding probability of 0.001 for a fit this bad or worse.[5]

Thus even if the incident pion, track 1, were missing we could reasonably conclude that event B is a leptonic decay of the Λ, with about 30 to 1 odds for beta decay as against muonic decay.

We next examine the kinematics of the decay $2 \rightarrow 3+4$, at B. We find that the beta decay $\Lambda \rightarrow p + e^- + \bar{\nu}$ satisfies energy and momentum conservation for a Λ of 650 Mev/c. The electron momentum in the Λ rest frame is 120 Mev/c, or about 72% of the allowed maximum momentum. A 650-Mev/c Λ at the observed production angle falls in the middle of the allowed region for indirect production via $\pi^- + p \rightarrow K^0 + \Sigma^0$, $\Sigma^0 \rightarrow \gamma + \Lambda$.

On the other hand, the muonic decay $\Lambda \rightarrow p + \mu^- + \bar{\nu}$ cannot conserve momentum and energy using the measured values. If one stretches the measured quantities so as to force momentum and energy conservation, and at the same time minimizes the overall chi square, one obtains a chi square of 2.6. The odds against the muonic decay mode are thereby increased by at least a factor of 10.

We have so far analyzed 689 Λ decays. Since about 38% of the time a Λ undergoes neutral decay, we can infer $[0.38/(1-0.38)] \times 689 = 422$ additional nonleptonic decays. We estimate that a muonic or a beta decay has a 10% chance of fitting a normal Λ decay and so escaping detection. Therefore we have observed an effective $0.9 \times 689 + 422 = 1042$ Λ decays, and found one beta decay and zero muonic decays.[6] The theory of Feynman and Gell-Mann predicts 16×10^{-3} and 3×10^{-3} for the respective probabilities.[7]

We wish to thank Luis W. Alvarez for his interest and guidance in the associated production experiment. We thank J. Don Gow and the bubble chamber crew, Hugh Bradner and the scanners, and Edward Lofgren and the Bevatron crew for the technical assistance which made this experiment possible.

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[1] An event whose most likely interpretation is $\Sigma^\pm \rightarrow e^\pm (\text{or } \mu^\pm) + n + \nu$ has been observed in nuclear emulsion by J. Hornbostel and E. O. Salant, Phys. Rev. 102, 502 (1956).

[2] If track 1 were not present, the decay at B would still be completely incompatible with K_1^0 decay; a normal Λ decay would fit, however, provided we neglected the important information obtained from vertex C.

[3] Willis, Fowler, and Rahm, Phys. Rev. 108, 1046 (1957).

[4] The relativistic ionization increase for a 210-Mev/c electron, as compared to a 210-Mev/c pion, is largely cancelled by the density effect.

[5] If one invokes a bremsstrahlung emission accompanying the electron-electron scatter, in order to

help balance transverse momentum, one obtains only a slightly improved fit.

[6] Out of 370 effective Λ decays, zero leptonic decays were found in a series of hydrogen and propane bubble chamber experiments by Eisler, Plano, Prodell, Samios, Schwartz, Steinberger, Conversi, Franzini, Manelli, Santangelo, and Silvestrini, Nevis Cyclotron Laboratory Report No. 67 (unpublished).

[7] R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958).

LEPTONIC DECAYS OF HYPERONS

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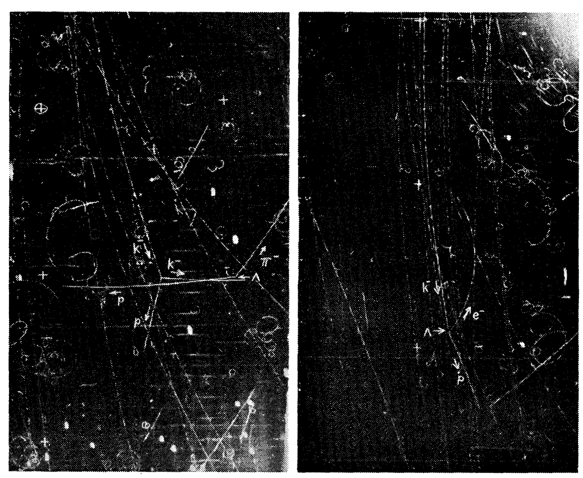
A few days after learning of the event reported in the preceding Letter one of us noticed another Λ beta decay. This second event was found in the film taken in the course of an experiment in which an electrostatically separated K^- beam[1] was passed into the Berkeley 15-inch hydrogen bubble chamber.

Our scanners have so far logged $\approx$7000 cases of hyperon production, among them almost 2000 Λ. A typical Λ production and decay is shown in Fig. 1 (a). The K happened to scatter on a proton before coming to rest, where it produced a Λ. In the course of measuring the K-p scatter, it was noticed that another event in the same picture [Fig. 1 (b)] could not possibly fit the common Λ-production and -decay process; if we restrict ourselves to well established particles we are forced to the conclusion that a Λ produced by the K^- decayed via the process $\Lambda \rightarrow p + e^- + \bar{\nu}$. The justification of this interpretation follows: The positive prong of the V must be a proton: it has high momentum, is heavily ionizing, and comes to rest in the chamber without producing any decay particles. The negative prong must be an electron, since we can show by range, curvature, and ionization that it is lighter than a muon. It left the chamber after a path length of 15 cm; a μ would have had an average momentum of at least 52 Mev/c, but the measured average momentum was 44 ± 2 Mev/c. In addition, careful examination of all four views indicates that the negative prong is very close to minimum ionization, while a nearly stopping μ would be several times minimum even at the vertex and would saturate within a few cm.

Having established the identity of the charged secondaries, we must show that the measured momenta and angles are compatible with the kinematics of a Λ produced in K^- capture and decaying via $\Lambda \rightarrow p + e^- + \bar{\nu}$. Analysis of the decay shows that the Λ had a momentum of 175 ± 100 Mev/c. This indeed overlaps the range of momentum of Λ produced in K^- capture by protons.

In order to establish a branching ratio of leptonic to pionic hyperon decay, one must estimate in what fraction of the cases one is able to distinguish the various modes. On careful analysis one can distinguish the leptonic from the pionic mode about 90% of the time. (Unfortunately we have so far analyzed only a small fraction of our data.) We also have a finite chance of recognizing "obvious" leptonic decays before they are measured, as is illustrated by the detection of the event described above. However, our detection efficiency for these "obvious" events depends on the alertness of our scanners and is hard to estimate.[2]

A summary of the present experimental status including the work of other laboratories is pre-



(a) (b)

FIG. 1. Normal and β decay of Λ. In the left-hand picture a K^- scatters on a proton before coming to rest and producing a Λ. The Λ decays via the normal mode, $\Lambda \rightarrow p + \pi^-$. Notice that the angle of the Λ decay includes the Λ direction of flight. The Λ in the right-hand picture decays via the leptonic mode, $\Lambda \rightarrow p + e^- + \bar{\nu}$. Note that the charged secondaries do not point back to the K^- ending, hence the decay is inconsistent with two-body kinematics. Both events are from the same bubble-chamber picture.

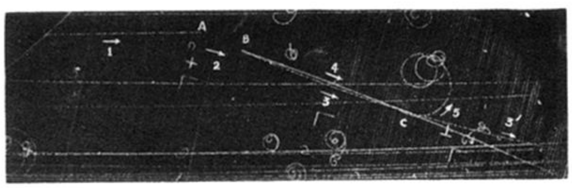


Fig. 1. Photograph of the event. The distance from vertex B to vertex C is 5 cm.