if the total cross section were geometric. In addition, two possible θ_1^0 regenerations were found.

All 23 events in which two strange particles originated in the same pion interaction were certain or probable hyperon-K meson associated productions. Only a few of these events are "simple" events; that is, are consistent with production by a single pion-nucleon collision. The fractions of the events which are simple agree well with those expected based upon our estimates of the θ^0-nucleon scattering and Σ^--proton charge exchange cross sections.

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Production of Strange Particles by 2.8-Bev Protons in C, Fe, and Pb†

THEODORE BOWEN, JUDSON HARDY, JR.,* GEORGE T. REYNOLDS, GUIDO TAGLIAFERRI,‡ AND ALBERT E. WERBROUCK
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

AND

WILLIAM H. MOORE
Brookhaven National Laboratory, Upton, New York

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Observations of Λ^0, θ_1^0, and $\Sigma_\pi^\pm$ particles from 2.8-Bev proton interactions have been made in a multiplate cloud chamber with one-half inch plates of C, Fe, and Pb. The $Y^0(\Lambda^0, \Sigma^0)$ and θ^0 cross sections, when compared with those observed for production by 1.5-Bev π^- mesons with the identical arrangement, are lower by at least a factor of four for C and a factor of two for Pb. Production of $\Sigma_\pi^\pm$'s by protons and pions seem to be of comparable magnitude in either C or Pb. Since protons are less effective than pions of similar kinetic energy (in the center-of-mass system) in producing strange particles, it is estimated in the case of incident protons that indirect production of strange particles by intermediate pions accounts for $(40_{-13}^{+28})\%$ of the observed particles in C and $(64_{-14}^{+21})\%$ in Pb. The different A dependence of the proton and pion cross sections for producing observable strange particles (Λ^0, θ_1^0, $\Sigma_\pi^\pm \to \pi^\pm + n$) may be fitted by a total proton-nucleon direct production cross section of 0.09 ± 0.06 mb.

The proton-produced strange particle events were used to compute what would be expected when decay γ rays emitted at 90° to the beam direction are observed in the geometry used by Berley and Collins. The predicted decay curve is in excellent agreement with their observations, and the absolute and relative yields agree within the estimated experimental uncertainties.

IN the earliest observations of Λ^0's, θ^0's, and $\Sigma^\pm$'s produced in Cosmotron beams, there was evidence that although the production cross section was ≈ 1 mb for 1.4-Bev π^--p collisions,[1] it was appreciably lower in 2.7-Bev p-p[2] and p-nucleus[3] collisions and in 1–2 Bev neutron-nucleus collisions.[4] The numbers of strange particles observed from protons and neutrons[3,4] on Pb were such as to be entirely attributable to indirect production by intermediate real pions in a two-stage process:

$$N+N \to N+N+n\pi, \quad (1)$$

$$\pi+N \to Y+K. \quad (2)$$

A direct strange particle production would be simply

$$N+N \to N+Y+K. \quad (3)$$

It was pointed out[5,6] that the indirect production

† Supported by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
* Now at Westinghouse Electric Corporation, Pittsburgh, Pennsylvania.
‡ Now at the Universita di Milano, Milan, Italy.
[1] W. B. Fowler, R. P. Shutt, A. M. Thorndike, and W. L. Whittemore, Phys. Rev. **91**, 1287 (1953); **93**, 861 (1954); **98**, 121 (1955).
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TABLE I. Numbers of strange particles observed from 2.8-Bev proton interactions.

Material		C			Fe[a]			Pb		
Number of nuclear interactions[b]			13 800			19 600			19 300	
Particle		Λ^0	θ_1^0	$\Sigma_\pi^{\pm}$ [c]	Λ^0	θ_1^0	$\Sigma_\pi^{\pm}$ [c]	Λ^0	θ_1^0	$\Sigma_\pi^{\pm}$ [c]
Weighted numbers of strange particles (actual numbers in parentheses)	Rating: Definite	4.6(1)	9.3(2)	0	55.4(6)	0	0	67.8(11)	25.4(3)	0
	Probable	17.8(3)	0	24.6(3)	9.9(2)	7.1(1)	4.0(1)	4.6(1)	12.1(3)	74.0(9)
	Ambiguous	5.7(1)			0			19.9(4)		
Strange particles per 1000 nuclear interactions	All events	1.9±0.9	0.8±0.5	1.8±1.4	3.3±1.6	0.4±0.4	0.2±0.2	4.5±1.4	2.2±1.0	3.8±2.7
	Events with $\|\lambda\| \geq 1$ cm	1.9±0.9	0.8±0.5	0.6±0.6	1.9±0.7	0.4±0.4	0.2±0.2	3.9±1.2	1.4±0.6	1.5±0.9

[a] Due to the closer plate spacing, results for strange particles from Fe are lower limits only.
[b] Calculated from track counts and total cross sections.
[c] $\Sigma_\pi^{\pm} \rightarrow \pi^{\pm}+n$ decay mode only.

would increase more rapidly with nuclear size than the direct because of the increasing average number of secondary pion interactions; however, this is modified by the interactions of the strange particles themselves within the production nucleus.

To learn the A dependence of strange-particle production, the yields from a 1.5-Bev π^- beam on C, Fe, Pb are compared with those from a nearly identical 2.8-Bev proton beam. The results from the π^- beam are discussed in the preceding paper,[7] hereafter referred to as I.

While the Princeton work was in progress, several other groups also investigated strange-particle production by 3-Bev protons. The Princeton cloud chamber shared the same pion and proton beams with the MIT multiplate cloud chamber with Fe plates,[8] also one-half inch thick, facilitating direct comparisons of results. A search for strange-particle production[9,10] in a hydrogen diffusion chamber using 2- and 3-Bev pencil beams produced one good example of Λ^0+K^++p at 2 Bev and one doubtful charged V at 3 Bev, further indicating a low cross section ($\approx$0.1 mb).

K^+ differential cross sections have been observed at zero degrees for several target elements,[11,12] including hydrogen. Total K^+ production cross sections resulting from assuming a matrix element which is constant or proportional to $P\cos\theta$ gave values comparable to the corresponding π-nucleus production for K^+, that is, substantially higher than the cloud chamber results for strange particle production by protons.

Observing γ rays emitted at 90° to the proton beam a few centimeters downstream from Cosmotron targets, Ridgway, Berley, and Collins[13,14] attribute them to π^0 decay modes of Λ^0, θ_1^0, and Σ^+ particles. Relative yields from targets (hydrogen to lead), when coupled with a knowledge of the lifetimes and branching ratios of these particles, make possible a detailed comparison with cloud-chamber results (see Sec. D).

Results from 7100 acceptable cloud-chamber expansions are presented in the following sections. The number of events is small because of the smaller production of strange particles by protons compared to pions and because of a premature termination of the experiments due to an extended Cosmotron shutdown.

A. EXPERIMENTAL ARRANGEMENT

Except for substituting a proton beam of 2.8±0.1 Bev, giving about the same center-of-mass kinetic energy in a collision with a nucleon as a 1.5-Bev pion, the experimental set up was identical to that in I. To avoid events due to secondary pions, the incoming track of an interaction was required to be within 7° of the average incoming beam direction. This criterion necessitated the exclusion of only two events. We believe that the contribution due to high-energy secondary pions in the beam was negligible. Identification procedures, event weights, and treatment of errors are described in I.

B. EXPERIMENTAL RESULTS

Table I lists the yields of proton-produced strange particles in C, Fe, and Pb. The total number of nuclear interactions produced in each material was calculated from the total number of beam tracks entering the chamber and from the attenuation and absorption cross sections determined from a portion of the pictures.[15] The symbol $\Sigma_\pi^{\pm}$, with the subscript π is used as only the charged pion decay mode can be identified. The weighted number of events in each identity category,

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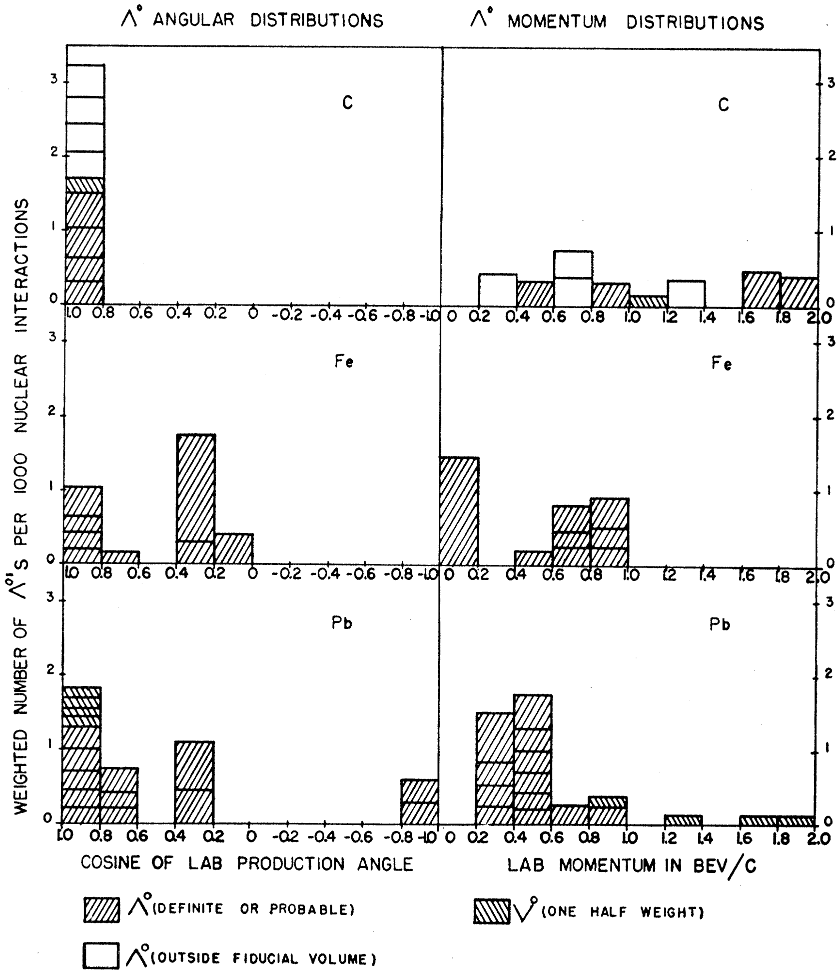

FIG. 1. Λ^0 production distributions by 2.8-Bev protons. Each rectangle represents one observed event.

as described in I, is given, with the actually observed number of events in parenthesis.[16] The yields are also given including only those events with a mean longitudinal decay length, λ, greater than 1 cm, since statistics of greater reliability result because of the high-detection efficiency for all such events.

Table I clearly shows that the number of strange particles per nuclear interaction increases by a factor of two from C to Pb which is consistent with the important role of indirect production.[5,6] The yield from Fe should be intermediate between C and Pb, but, as stated in I, the closeness of the Fe plates greatly reduced the scanning efficiency. The comparison between C and Pb is much more reliable because the greater spacing of the plates permitted a fiducial volume at greater distances from the plates and most of the events were

TABLE II. Strange-particle production cross sections by 2.8-Bev protons. (All figures are mb.)

	C			Fe[a]			Pb		
Nuclear absorption cross section[b]		230±12			690±28			1630±75	
Particle	Y^0	θ^0	$\Sigma_\pi^{\pm c}$	Y^0	θ^0	$\Sigma_\pi^{\pm c}$	Y^0	θ^0	$\Sigma_\pi^{\pm c}$
All events	0.44±0.20	0.37±0.23	0.41±0.33	2.3±1.1	0.5±0.5	0.14±0.14	7.4±2.3	7.2±3.4	6.2±4.4
Events with $\|\lambda\| \geqslant 1$ cm	0.44±0.20	0.37±0.23	0.14±0.14	1.3±0.5	0.5±0.5	0.14±0.14	6.3±2.0	4.4±1.9	2.4±1.4

[a] Due to the closer plate spacing, results for strange particles from Fe are lower limits only.
[b] See reference 15.
[c] $\Sigma_\pi^\pm \rightarrow \pi^\pm + n$ decay mode only.

[16] The following decay lifetimes were assumed (in units of 10^{-10} second): Λ^0, 2.77; θ_1^0, 0.95; Σ^-, 1.7; Σ^+, 0.75.

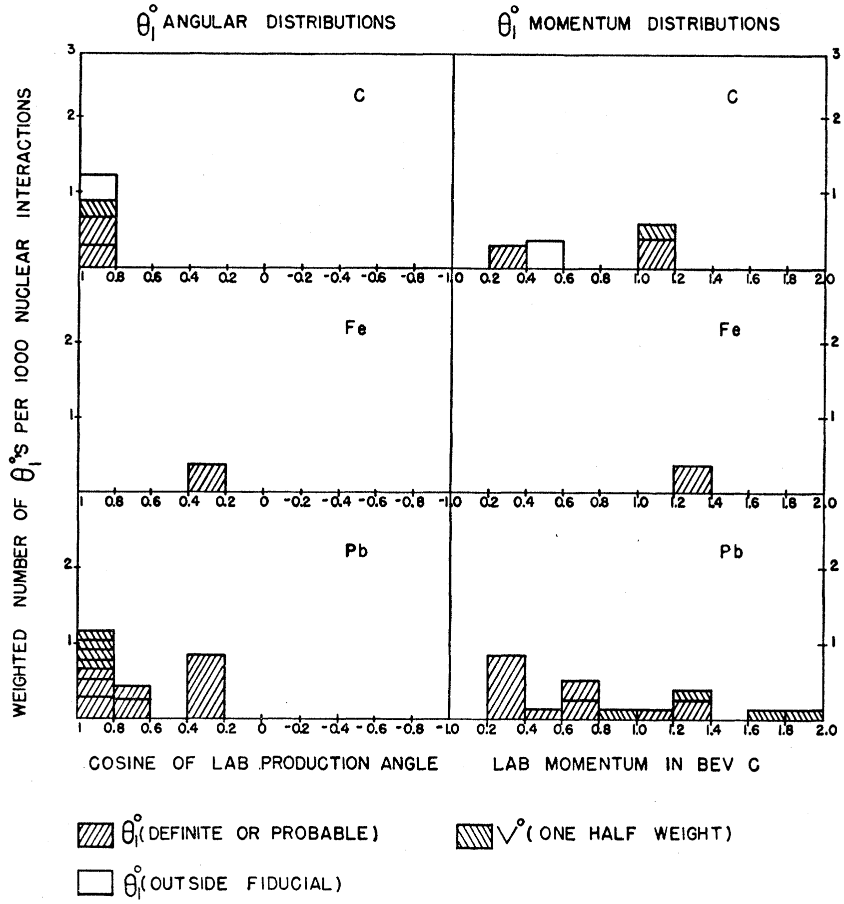

FIG. 2. θ_1^0 production distributions by 2.8-Bev protons. Each rectangle represents one observed event.

found in plate assemblies in which C and Pb were intermixed.

In Table II the total cross sections for Y^0, θ^0, and $\Sigma_\pi^\pm$ production are compared with total nuclear absorption cross sections for protons on the target elements. (Y^0 refers to the combined Λ^0 and Σ^0 production inferred from the observed Λ^0 decays.) A comparison is given in Table III with other results from 3-Bev p-Fe collisions. An interpolation between our more reliable C and Pb cross sections is also given. The BNL values, although substantially higher, appear to be consistent, since the errors are large.

Figures 1, 2, and 3 are the histograms of the observed laboratory angular and momentum distributions for Λ^0, θ_1^0, and $\Sigma_\pi^\pm$ production, where the heights are proportional to the assigned weight and ambiguous events (V^0's) are plotted equally on the Λ^0 and θ_1^0 histograms with half weight. Since few C events were found within the fiducial volume for cross section determinations, events found outside this volume are also indicated.

TABLE III. Comparison of strange-particle production cross sections by 2.8-Bev protons in Fe. (Cross sections in mb.)

Source	Y^0	θ^0	$\Sigma_\pi^\pm \to \pi^\pm + n$
MIT (Fe)[a]	$1.7_{-0.6}^{+1.7}$	$3.3_{-1.1}^{+3.5}$	1.4 ± 0.7
Princeton (interpolation between C and Pb)	2.2 ± 0.6	2.1 ± 0.8	1.9 ± 1.0
Princeton (Fe, lower limit only)	2.3 ± 1.1	0.5 ± 0.5	0.14 ± 0.14
BNL (Fe in pencil[b] beam)	5.5 ± 1.5	6.0 ± 2.0	0.9 ± 0.5

[a] E. Boldt, H. S. Bridge, D. O. Caldwell, and Y. Pal (private communication).
[b] See reference 10.

Figures 1 and 2 show evidence of secondary processes within the production nucleus such as nuclear scattering and $\Sigma \to \Lambda^0$ conversions. For both the Λ^0 and θ_1^0, the angular distribution is broadened with increasing nuclear complexity and the momentum of the particles emerging from complex nuclei appears to be lowered. The charged $\Sigma_\pi^\pm$'s do not show a change from C to Pb, which is reasonable if, as discussed in I, the $\Sigma^\pm$ charge exchange cross section is large. Secondary processes are in evidence in C where two out of the three events are incompatible with production in a single p-nuclfon collision and the angular distribution from Pb indicates that secondary interactions were involved in most cases.

C. A-DEPENDENCE OF STRANGE PARTICLE PRODUCTION

Table I indicates that there is an increase ın strange-particle production per nuclear interaction from C to

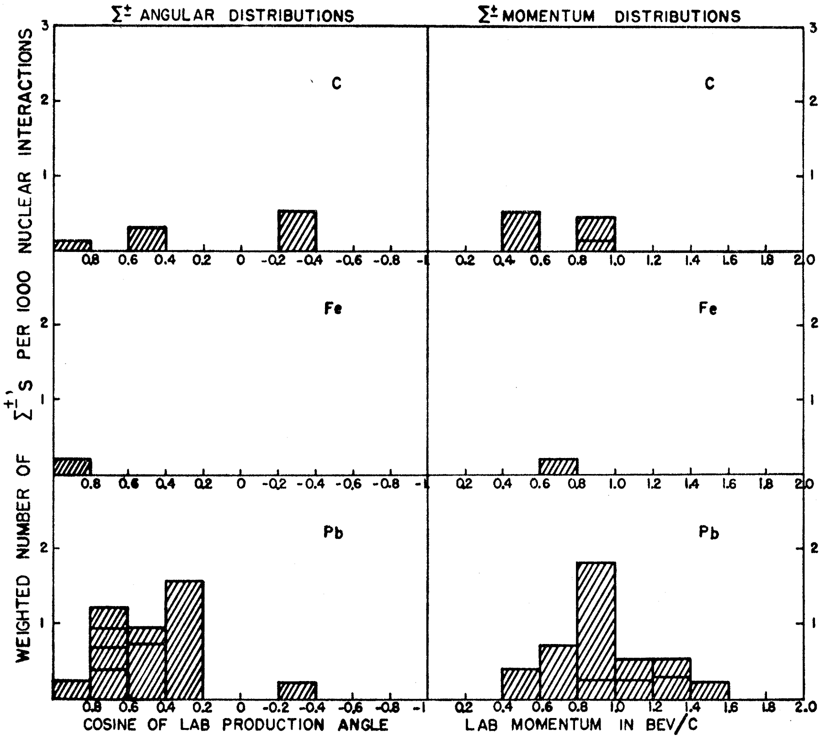

FIG. 3. $\Sigma_\pi^\pm \to \pi^\pm + n$ production distributions by 2.8-Bev protons. Each rectangle represents one observed event.

Pb, but the statistical uncertainties are large, especially if the events are divided into Λ^0's, θ_1^0's, and $\Sigma_\pi^\pm$'s. For example, because of ambiguity in identification, the A-dependence of the θ_1^0's could be completely altered by changing the interpretation of a few C events. A better measure of the A-dependence of strange particle production is obtained if the Λ^0 and θ_1^0 events are grouped together, since the assigned weight of each V^0 event is about the same whether interpreted as a Λ^0 or θ_1^0. We obtain a still better measure of strange particle production by grouping Λ^0, θ_1^0, and $\Sigma_\pi^\pm$, which minimizes the sensitivity of the observed A dependence upon Σ-to-Λ^0 conversions. The A dependence of $(\Lambda^0+\theta_1^0+\Sigma_\pi^\pm)$ will not be greatly influenced by charge exchange of θ_1^0's because even their total interaction cross section is small.[17]

All strange particle yields discussed in this section will refer to the numbers of $\Lambda^0+\theta_1^0+\Sigma_\pi^\pm$ with $|\lambda| \geqslant 1$ cm per 1000 inelastic nuclear interactions, which will give a measure of the probabilities for associated hyperon-K production in nuclear collisions with complex nuclei with a minimum of statistical fluctuation. These yields from both pions and protons are listed in Table IV. Whereas the yield from pion collisions is independent of A, the yield from the proton collisions, though appreciably less, increases significantly from C to Pb.

[17] M. N. Whitehead, R. W. Birge, W. B. Fowler, R. E. Lanou, and W. M. Powell, Bull. Am. Phys. Soc. **3**, 24 (1958); H. C. Burrowes, D. O. Caldwell, D. H. Frisch, D. A. Hill, D. M. Ritson, and R. A. Schluter, Phys. Rev. Letters **2**, 117 (1959).

It is of interest to interpret these yields in terms of elementary collision processes which occur within the nucleus, particularly the magnitude of direct proton-nucleon production for strange particles and the relative amount of direct and indirect production in C and Pb. To do this, the nuclear cascades were studied in a simple one dimensional model representing the nucleus by a sphere of uniform density. Radii were so chosen that, together with the pion or proton cross sections listed in Table V, the total cross sections agree with the measured values.[15,18] The estimates of Fowler, Taft, and Mosburg[19] were used for the production of high-energy pions by protons, and for the production of strange particles by pions. Collisions of π^--p[20] and π^--nitrogen[21] at 1.4 Bev, in

TABLE IV. Yields of $\Lambda^0+\theta_1^0+(\Sigma_\pi^\pm \to \pi^\pm+n)$ from pion and proton interactions. (Number observed per 1000 nuclear interactions.)

Material	1.5-Bev π^-	2.8-Bev protons
C	25.7±3.6	3.33±1.18
Fe[a]	22.5±4.1	2.46±0.85
Pb	21.7±1.8	6.68±1.61

[a] Due to the closer plate spacing, results for Fe are lower limits only.

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[20] L. M. Eisberg, W. B. Fowler, R. M. Lea, W. D. Shephard, R. P. Shutt, A. M. Thorndike, and W. L. Whittemore, Phys. Rev. **97**, 797 (1955).

[21] G. D. Gordon, R. H. Milburn, J. C. Street, and L. A. Young, Phys. Rev. **108**, 1315 (1957).

TABLE V. Parameters in one-dimensional nuclear cascade.

	1.5-Bev π^-	2.8-Bev protons
σ_{total} (mb)	33	38
$\sigma_{inelastic}$ (mb)	25	25

combination with the isobar model, have been used to estimate the production by pions of pions above the strange particle threshold. It was estimated that about one-half of the inelastic π^--nucleon collisions at 1.5 Bev lead to another pion with sufficient energy to produce strange particles. The small effect of the different neutron-proton ratios was included.

These assumptions enable us to predict pion yields and indirect yields from proton collisions. Before comparing with observations, however, complications due to the finite plate thickness must be taken into account. The kinematics of strange particle production are such that all hyperons and most θ^0's have $|\lambda| \geqslant 1$ cm in the laboratory and that particles with $|\lambda| < 1$ cm, which are not included in the observations, result from the interaction of strange particles before escaping from the production nucleus. This suggests that scattering or charge exchange of strange particles within the production nucleus might be the most important cause for removal of particles from observation. To allow for this, a phenomenological strange particle-nucleon removal cross section, σ_a, is introduced. There is no *a priori* reason that σ_a should have the same value for Λ^0, Σ^0, θ_1^0, and $\Sigma_\pi^\pm$. However, if we examine a portion of the data where σ_a exerts the greatest effect and where there are the best statistics, π^- on Pb, interpolation over $-1 < \lambda < +1$ shows that 18% of the Λ^0's and 22% of the θ_1^0's fall into the $|\lambda| < 1$ cm group, i.e., losses of Λ^0 and θ_1^0 particles are of the same magnitude. From these figures, a lower limit, $\sigma_a \geqslant 2.3 \pm 1.6$ mb, has been estimated, since charge exchange and nuclear capture have been ignored. Other upper and lower limits on σ_a from pion and proton data have been obtained which still allow a reasonable agreement between the observed and calculated A dependence of strange particle yields (see Fig. 7).

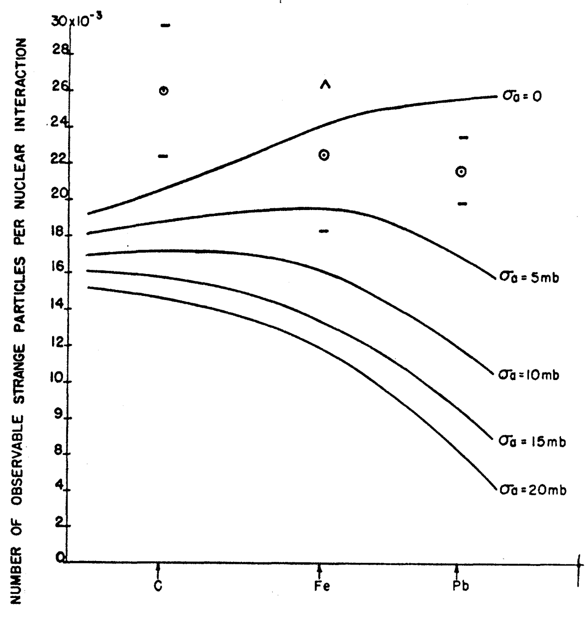

FIG. 4. The number of observable strange particles (Λ^0, θ_1^0, $\Sigma_\pi^\pm \rightarrow \pi^\pm + n$) produced by 1.5-Bev π^- predicted by a one-dimensional model of the nuclear cascade for several values of the removal cross section, σ_a, defined in the text (Sec. C). The points represent the yields observed in I.

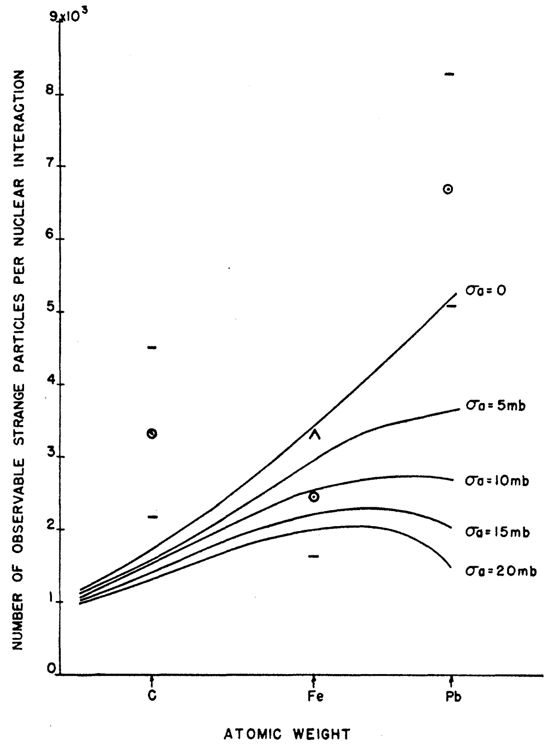

FIG. 5. The number of indirectly produced observable strange particles (Λ^0, θ_1^0, $\Sigma_\pi^\pm \rightarrow \pi^\pm + n$) from 2.8-Bev proton collisions predicted by a one-dimensional model of the nuclear cascade for several values of σ_a. The points represent the total yields observed in this experiment.

Figure 4 compares the strange particle yield from pions as a function of A with observation. Without adjustment of the absolute strange particle production cross section, Fig. 4 shows that $1 \leqslant \sigma_a \leqslant 5$ mb gives reasonable agreement with observation, and, if only the C to Pb yield ratio is considered, $\sigma_a = 6 \pm 3$ mb. The satisfactory agreement with pion yields encourages the use of the one-dimensional model to estimate indirect production by protons.

Figure 5 compares the yields of indirectly produced strange particles in 2.8-Bev proton collisions as a function of A with the observed total yields. Even in C, one-half of the yield could be from indirect production.

Since direct production should be nearly independent of A, the equal displacement of the observed C and Pb yields above $\sigma_a \approx 5$ mb could be interpreted as resulting from direct production. It must be emphasized that in addition to the assumptions which entered into the comparison of the pion results (Fig. 4), the proton indirect yield depends directly on the assumed fraction (0.38) of the inelastic proton collisions which lead to a pion with energy above strange particle production threshold.

Yield curves for direct and indirect production by protons for various σ_a's are shown in Fig. 6. For direct production, the ordinate gives the number of strange particles per interaction if each inelastic p-nucleon collision produces exactly one strange particle. For indirect production, the ordinate is the same if each inelastic p-nucleon collision yields one pion of production energy and if each π-nucleon collision yields one strange particle.

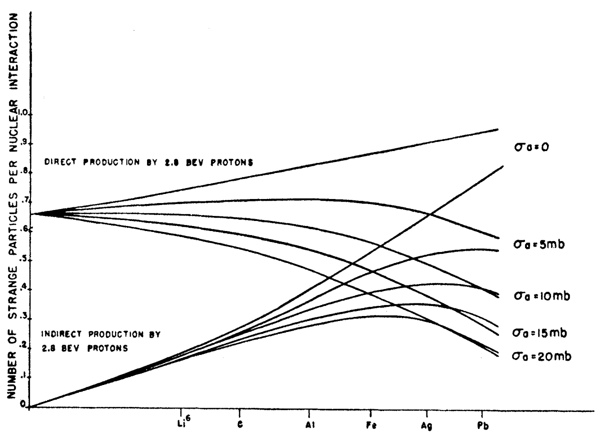

FIG. 6. Curves of the direct and indirect production of strange particles predicted by a one-dimensional model of the nuclear cascade for several values of σ_a. For the units of the ordinate, see the text (Sec. C).

To estimate the direct production from Fig. 5 for any σ_a, the corresponding curve from Fig. 6 must be multiplied by a factor such that when added to the indirect production curve in Fig. 5, the sum will best fit the observed points. In estimating errors, an error of $\pm 30\%$ was assigned to the normalizing factor (0.38) for indirect production. The results are shown in Fig. 7. The vertical lines give the limits on σ_a. For example if $\sigma_a > 7.5$ mb (Limit C), the proton-produced yields vary in a manner contrary to observed yields. Since σ_a accounts for a loss of events caused by the presence of our chamber plates, it is not of general interest. The cross section, $\bar{\sigma}_v$, gives the total production of Λ^0, θ_1^0, and $\Sigma_\pi^\pm$ particles by 2.8-Bev protons on nucleons, i.e., for an averaged nuclear mixture of 45% protons. Any combination of $\bar{\sigma}_v$ and σ_a in the shaded region gives satisfactory agreement with the observed yields. We find

$$\bar{\sigma}_v(p\text{-}N) = 0.09 \pm 0.06 \text{ mb}.$$

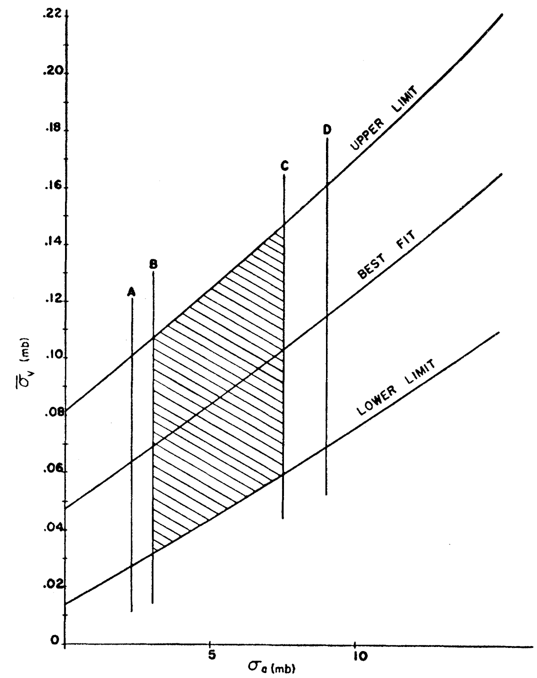

FIG. 7. The proton-nucleon direct cross section, $\bar{\sigma}_v$, for strange particle (Λ^0, θ_1^0, $\Sigma_\pi^\pm$) production obtained from the A dependance of the yields, as a function of the assumed value of σ_a. A: Lower limit on σ_a from a direct estimate of unseen events in π^- on Pb. B: Lower limit on σ_a for internal consistency of π^- data. C: Upper limit on σ_a for internal consistency of proton data. D: Upper limit on σ_a for internal consistency of π^- data.

The results of other experiments on p-p collisions are given in Table VI, and, for comparison, the corresponding yields from π-nucleon collisions, which appear to be significantly greater.

By a similar analysis, an estimate can be made for the fraction of the yields from C and Pb due to indirect production. The results are shown in Fig. 8, and again depend upon the assumed value of σ_a. Using the region bounded by the limits on σ_a, we find that $(40_{-13}^{+28})\%$ of the strange particles from C are indirectly produced, which increases to $(64_{-14}^{+21})\%$ for Pb. In agreement with earlier work,[2,3] indirect production of strange particles is always important in complex nuclei bombarded by 2.8-Bev protons.

TABLE VI. Comparison of proton-nucleon and pion-nucleon production of $\Lambda^0 + \theta_1^0 + \Sigma_\pi^\pm$.

Source	Colliding particles	Total strange particle cross section,[a] $\bar{\sigma}_v$ (mb)
Princeton (C and Pb)	p-N[b]	0.09 ± 0.06
BNL (H_2)[c]	p-p	$0.04_{-0.04}^{+0.1}$
Bubble chamber results and charge independence[d]	π^+-N	0.36
	π^0-N	0.57
	π^--N	0.49

[a] Note that these are not total associated production cross sections in the usual sense, but refer to the combined number of Λ^0's, θ_1^0's, and $\Sigma_\pi^\pm \to \pi^\pm + n$; hence, $\bar{\sigma}_v(\pi^0 - N) \neq \frac{1}{2}[\bar{\sigma}_v(\pi^+ - N) + \bar{\sigma}_v(\pi^- - N)]$.
[b] $N \equiv$ Average nucleon in a nucleus (about 45% protons, 55% neutrons).
[c] See reference 10.
[d] See reference 19.

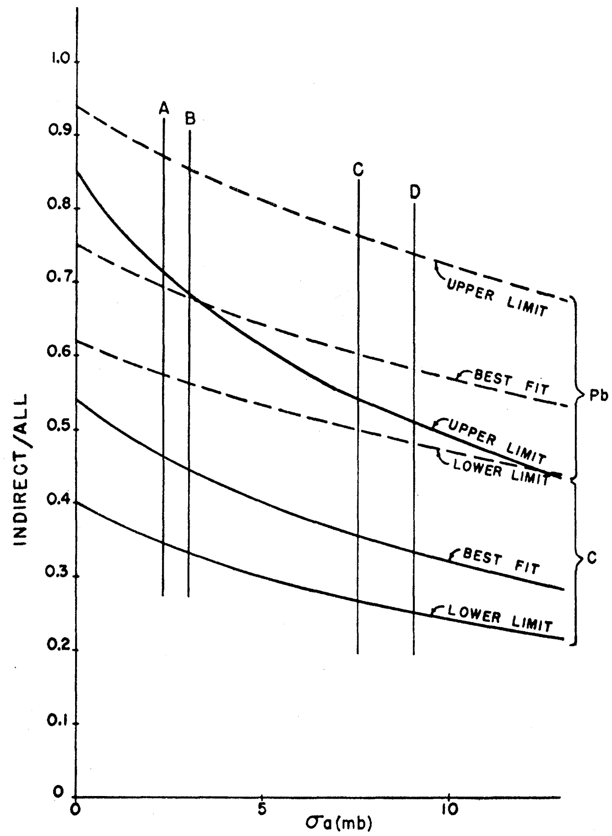

FIG. 8. The fraction of observable strange particles (Λ^0, θ_1^0, $\Sigma_\pi^\pm \rightarrow \pi^\pm + n$) due to indirect production as a function of the assumed value of σ_a. The limits, *A*, *B*, *C*, *D* are the same as in Fig. 7. The solid curves are for production in C, the dashed for production in Pb.

D. COMPARISON WITH THE OBSERVATION OF DECAY γ RAYS

Since there is still very little information available on the production of strange particles by $\approx$3-Bev protons, it is of interest to make a detailed comparison between the cloud chamber observations and the observations initiated by Ridgway, Berley, and Collins[13] and extended to cover most of the periodic table by Berley and Collins[14] of γ rays emitted at 90° from points downstream from internal Cosmotron targets. They have interpreted these γ rays as due to the decay of strange particles (Λ^0, θ_1^0, Σ^+) into π^0 modes, the π^0's then decaying into γ rays. However, there was no evidence from their work as to the relative contributions from Λ^0, θ_1^0, and Σ^+ decays. Even the evidence that the γ's are indeed due to strange particle decays was of an indirect nature, relying upon an analysis of the excitation curve as a function of proton energy. In addition to the 26 Λ^0's, 12 θ_1^0's, and 13 $\Sigma_\pi^\pm$'s from C, Fe, and Pb in the Princeton data, 9 Λ^0's, 8 θ_1^0's, and 8 $\Sigma_\pi^\pm$ from Fe found by the MIT group[8,22] have been included in making the comparisons of this section.

[22] E. Boldt (private communication).

The method of comparison[23] relied upon the fact that the γ rays were counted in a known geometry and that the threshold of the γ counter was low enough ($\approx$10 Mev) so that the detection efficiency was essentially constant independent of γ-ray energy. For each of the 35 Λ^0's, 20 θ_1^0's, and 21 $\Sigma_\pi^\pm$'s observed in the cloud chambers, the probability of counting a γ ray was calculated for several target-to-occulter distances. Using the weights assigned to particular events, a weighted average was computed to give the number of γ counts per observed Λ^0, θ_1^0, or $\Sigma_\pi^\pm$ (assumed to be Σ^+) to be expected. Using the total path length of C, Fe, or Pb traversed by protons, the number of γ counts per proton-g/cm^2 can be predicted.

Comparisons between target elements were calculated for the standard distance adopted by Berley and Collins of 1.6 cm from target to occulter; that is, from the downstream edge of the target to the upstream edge of the region viewed by the γ counter. The decay branching ratios are based upon the Berkeley results.[24] Since the cloud chambers had no magnetic fields, most $\Sigma^+ \rightarrow p + \pi^0$ decays are indistinguishable from $\pi^\pm \rightarrow \mu^\pm + \nu$ decays. Therefore, we have used all $\Sigma_\pi^\pm \rightarrow \pi^\pm + n$ decays and, assuming they are Σ^+'s, we have computed the γ yields to be expected. The total yield of Λ^0, θ_1^0, and Σ^+ includes only one-half the computed $\Sigma_\pi^\pm$ contibution, the other half being added to the quoted error, since we do not know the composition of the $\Sigma_\pi^\pm$ sample. The excess of positive charge in the primary collision might lead us to expect mainly Σ^+'s. Also, in the observations of Cool *et al.*[10] of strange par-

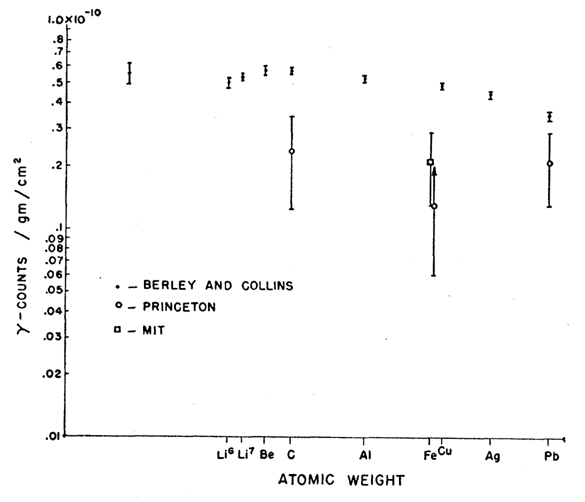

FIG. 9. The number of γ counts per g/cm^2 of target traversed by a proton observed by Berley and Collins, and the predicted counts based upon the events observed in the Princeton and MIT cloud chambers and the presently accepted decay lifetimes and branching ratios of strange particles.

[23] T. Bowen, Technical Report No. 24, Elementary Particles Laboratory, Princeton University, 1959 (unpublished). This report outlines the method of comparison in more detail.

[24] F. S. Crawford, M. Cresti, R. L. Douglass, M. L. Good, G. R. Kalbfleisch, M. L. Stevenson, and H. Ticho, Phys. Rev. Letters 2, 266 (1959).

ticles produced in an Fe foil in a diffusion cloud chamber in a 3-Bev pencil beam of protons, 5 Σ^+'s and 1 Σ^- were seen. The error in the final result from ambiguous V^0 events is small compared with the statistical error.

The total predicted and observed γ yields are plotted in Fig. 9 for comparison. It is seen that the dependence upon atomic weight is in good agreement, but the predicted yields are lower by a factor of about two. A discrepancy of this magnitude is not surprising, since Berley and Collins estimated that their absolute yields were accurate to within a factor of two, while the relative yields were limited in accuracy mainly by the counting statistics. The known factors contributing to errors in the absolute yields are: slit widths, counter efficiency, proton beam monitor calibration, and multiple traversals of the target. A correspondingly high absolute error in the cloud chamber results seems unlikely, although the direction of the discrepancy is the same as would be caused by scanning inefficiency. Due to the closer plate spacing we regard the Princeton Fe results only as a lower limit. However, since all the film was scanned twice, since the MIT and Princeton data appear to agree satisfactorily, and since the production cross sections in the π^- beam appear to agree well with those expected from bubble chamber results, a large absolute error in the cloud-chamber findings is unlikely (see Sec. C).

From Fig. 9 we see that the yield of γ rays per g/cm^2 of target remains roughly constant from carbon to lead. Since Berley and Collins observed that the γ count vs target-to-occulter distance distribution was independent of the target material, corresponding to a decay length of about 4 cm in each case, and we find that the relative Λ^0, θ_1^0, and $\Sigma^\pm$ contributions remain similar from C to Pb, it seems justifiable to combine the events from all materials (C, Fe, Pb) to predict the decay distribution.

In Fig. 10, the decay curves of the Λ^0, θ_1^0, and $\Sigma_\pi^\pm$ components predicted from the cloud-chamber events are shown, each normalized to its respective number of observed cloud-chamber events. It is at once noticed that the Λ^0- and θ_1^0-dacay curves are almost indistinguishable in shape. Hence, at ≈ 3 Bev, we cannot expect the arrangement of Berley and Collins to yield information about the relative numbers of Λ^0's and θ_1^0's from the downstream distribution of γ rays. In a similar experiment to observe γ rays from strange-particle decays at the Bevatron, Osher *et al.*[25] distinguish the Λ^0 and θ_1^0 components by using a γ counter with a threshold at much higher energy, which strongly favors the γ rays from θ_1^0 decay.

Also in Fig. 10, the sums $\Lambda^0+\theta_1^0$ and $\Lambda^0+\theta_1^0+\Sigma_\pi^\pm$ computed from the cloud-chamber events are shown, along with γ-ray yields actually observed by Berley and Collins from Cu and Pb. Since the Σ^+'s constitute some fraction of the $\Sigma_\pi^\pm$ sample, we might expect the correct

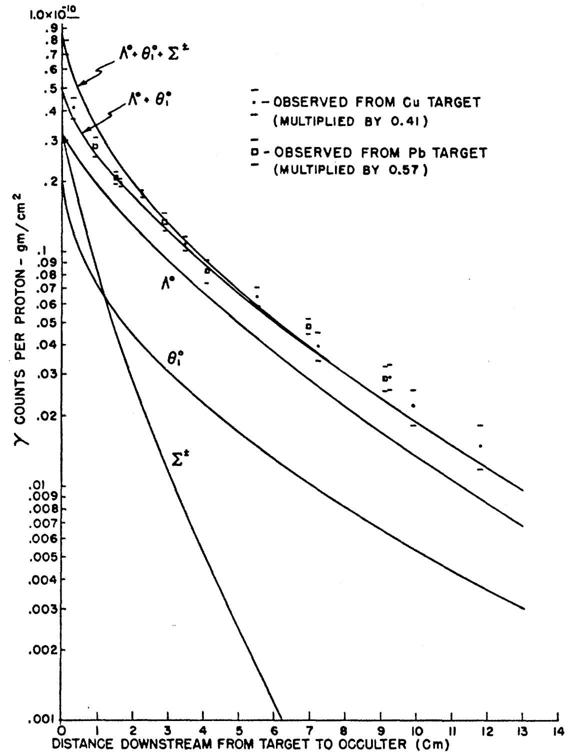

FIG. 10. The yield of γ rays which would be counted in the geometry of Berley and Collins as a function of distance downstream from the target due to the Λ^0, θ_1^0, and $\Sigma_\pi^\pm$ components. The combined curves, $\Lambda^0+\theta_1^0$ and $\Lambda^0+\theta_1^0+\Sigma_\pi^\pm$, are compared with the observed variation in yields from Cu and Pb targets.

decay curve to lie somewhere between the $\Lambda^0+\theta_1^0$ and $\Lambda^0+\theta_1^0+\Sigma_\pi^\pm$ curves. The data of Berley and Collins for Cu and Pb have been normalized for a best fit to the expected decay curve, since we expect only order of magnitude agreement in the predicted and observed absolute yields. The agreement in the shape of the decay curve appears to be excellent. The observed decay distributions appear to be consistent with any assumed fraction of Σ^+'s in the $\Sigma_\pi^\pm$ sample. A larger Σ^+ component than indicated by the cloud-chamber data would bring disagreement with the decay curve. Figure 10 indicates that even at the standard distance of 1.6 cm chosen by Berley and Collins for comparisons, the Λ^0 component accounts for at least half the γ counts, and up to three-quarters at larger distances. It should be emphasized that no particular significance should be attached to the exact slope and shape of the curve, as it depends not only upon the characteristics of the production and decay processes, but also upon the geometry in which the γ's are observed.

E. CONCLUSIONS

The production of Λ^0's and θ_1^0's from C, Fe, and Pb is significantly less in the 2.8-Bev proton beam than in the 1.5-Bev π^- beam. The observed yields are in good agreement with the cloud chamber observations of

[25] J. E. Osher, B. J. Moyer, and S. I. Parker, Phys. Rev. **114**, 612 (1959).

others. The total cross section for production of observable strange particles by protons increases more rapidly with A, from C to Pb, than in the case of production by pions. The lower cross section and more rapid variation with A indicate that indirect production of strange particles by intermediate pions accounts for a significant fraction of all strange particles produced by protons, even in carbon. An estimate of the total proton-nucleon direct production of observable strange particles ($\Lambda^0, \theta_1^0, \Sigma_\pi^\pm \rightarrow \pi^\pm + n$) giving a reasonable fit to the observed cross sections is 0.09 ± 0.06 mb.

A comparison of the cloud chamber results with the γ-ray yields observed at 90° from points downstream from Cosmotron targets indicates satisfactory agreement between the results of the two entirely different techniques of observing strange particle production. This strengthens the evidence that the γ rays are indeed the result of strange particle decays. The observed A dependence is in good agreement, giving greater weight to the cloud-chamber evidence that strange-particle production increases more rapidly with A than the total inelastic cross section from C to Pb.

It is hoped that the angular and momentum distributions will serve as a guide to those who contemplate experiments making use of strange particles produced by $\approx$3-Bev protons. Preliminary results from a Monte Carlo calculation carried out on the Los Alamos Maniac II[26] indicate that the present results on complex nuclei can be understood in terms of a cascade of individual particle-nucleon collisions with nucleons within the nucleus. The reliability of such a calculation to predict strange particle production from a proton-nucleus collision should improve as more observations are made of p-p and p-d collisions, and as more is known about strange-particle nucleon interactions. Proton-nucleus collisions at $\approx$3 Bev are not as suitable as pion-nucleus collisions for gaining information about strange-particle nucleon interactions, since the production cross sections are smaller, and the cascade of nuclear collisions involved is more complicated.

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[26] L. Sartori, A. E. Werbrouck, J. K. Wooten, and R. L. Bivins, Bull. Am. Phys. Soc. 4, 289 (1959).

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Branching Ratio of the Electronic Mode of Positive Pion Decay*

H. L. ANDERSON, T. FUJII, R. H. MILLER,† AND L. TAU‡
The Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois

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A new measurement of the branching ratio $(\pi^+ \rightarrow e^+ + \nu)/(\pi^+ \rightarrow \mu^+ + \nu)$ has been completed. A double-focussing magnetic spectrometer was used to observe the spectra of electrons emitted in π decay and in μ decay. The scintillation pulses from the pion and its decay electron were recorded on a travelling-wave oscilloscope. Timing and pulse-height measurements were used to distinguish good events from accidentals. The total number of π-e events recorded in this experiment was 1346, of which 6% were accidentals and 5% were π-μ-e contamination. The branching ratio obtained from an analysis of the data over the π-e and μ-e distributions and corrected to include all decay electrons was $(1.21 \pm 0.07) \times 10^{-4}$. This is close to the result expected for a universal V-A interaction. Kinoshita's calculation, taking into account radiative effects, gave 1.23×10^{-4}. Our data also gave for the mean life of π decay $\tau_\pi = (25.6 \pm 0.8) \times 10^{-9}$ second.

INTRODUCTION

THE charged pion normally decays into a muon and a light neutral particle, presumed to be a neutrino. The alternative decay mode, into an electron instead of a muon, was shown by earlier measurements to have a small branching ratio. Friedman and Rainwater[1] examining pion endings in photographic emulsion could report zero or one such decay in 1419 muonic decays. Subsequently, Lokanathan and Steinberger,[2] using a counter telescope arrangement, sensitive to the higher energy and shorter lifetime of the π decay to discriminate against the electrons from μ decay, reported a branching ratio $f = (-3 \pm 9) \times 10^{-5}$. In this laboratory, Anderson and Lattes[3] using a magnetic spectrometer to single out the electrons of π decay also failed to find the electronic mode. They reported a

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† Now at Yerkes Observatory, the University of Chicago, Chicago, Illinois.
‡ Now at Institute of Physics, University of Rome, Rome, Italy.

[1] H. L. Friedman and J. Rainwater, Phys. Rev. 84, 684 (1949).

[2] S. Lokanathan and J. Steinberger, Suppl. Nuovo cimento 1, 151 (1955).

[3] H. L. Anderson and C. M. G. Lattes, Nuovo cimento 6, 1356 (1957).