and the weighted mean is

$$\Lambda_c = 1520 \pm 50 \text{ sec}^{-1}.$$

The rate measured by Falomkin et al. using a He^3 diffusion chamber[3] ($\Lambda_c = 1410 \pm 140$ sec^{-1}) is consistent with our results. On the basis of the universal Fermi interaction, and using the most recent values of the He^3 rms radius obtained from electron-scattering experiments,[4] Wolfenstein predicted a rate of[5]

$$\Lambda_c = 1450 \text{ sec}^{-1}.$$

The error in the theory is difficult to estimate, but including the uncertainties in the triton *ft* value, the He^3 radius, and the magnitude of the induced pseudoscalar coupling, it may be as high as 10%.[1] The result of our experiment agrees well with the prediction of the universal Fermi interaction.

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RESOLUTION OF THE Σ^--MASS ANOMALY

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The masses of the charged Σ hyperons and the K^- meson are determined most accurately from range measurements in emulsion on the products of the following processes: (1) $\Sigma^+ \to p + \pi^0$, (2) $\Sigma^+ \to n + \pi^+$, (3) $K^- + p \to \Sigma^+ + \pi^-$, and (4) $K^- + p \to \Sigma^- + \pi^+$. Prior to 1960 the masses were determined, but not overdetermined, from the ranges of the charged baryons alone. The Σ^+ mass was found from the proton range in Reaction (1). The K^- mass was determined from the Σ^+ range in Reaction (3), and the Σ^- - Σ^+ mass difference was deduced from the Σ^+ - Σ^- range difference in Reactions (3) and (4). For such measurements, events are used in which the Σ^+ decays at rest and in which the K^- is captured by a free proton after it comes to rest.

In 1959-1960 we began measurements of the pion ranges with a dual purpose: to confirm the measurements by overdetermining the masses, and to study further the high-velocity range-energy relation in emulsion. We soon found[1] that there was an apparent lack of momentum balance in Reaction (4), although the other reactions seemed to balance satisfactorily.

We have recently carried out new measurements in a large emulsion stack. The results are practically identical with those reported previously, and we cannot doubt now that a real effect exists.[1-3] In this Letter we present our data, and propose that a physical effect not heretofore adduced is the reason for the measurement contradictions. We suggest that slow negative hyperons lose energy at a lower rate than do positive particles of the same velocity. We believe that an inequality in the energy-loss rates of positive and negative particles can be explained by extending the theory of stopping to include second-order Born approximation terms. This means that the existing range-energy (RE) relation,[4,5] which is based on positive-particle ranges, will not give

Table I. Observed ranges.

Process	Measured	Mean range	Number of emulsion stacks used
(1) $\Sigma^+ \rightarrow p + \pi^0$	$144 p$	1677 ±2 μ	5
(2) $\Sigma^+ \rightarrow n + \pi^+$	$48 \pi^+$	92.74 ±0.34 mm	2
(3) $K + p \rightarrow \Sigma^+ + \pi^-$	$40 \Sigma^+$	818.8 ±1.7 μ	6
	$24 \pi^-$	88.58 ±0.51 mm	3
(4) $K + p \rightarrow \Sigma^- + \pi^+$	$94 \Sigma^-$	708.9 ±1.5 μ	6
	$63 \pi^+$	78.45 ±0.25 mm	3

correct values for quantities derived from the Σ^- range in (4). We are led to this conclusion after rejecting several alternative possibilities, none of which could be made at all compatible with our understanding of the measurement errors.

Our ranges in emulsion of specific gravity 3.815 are given in Table I. The standard deviation of each range is in close agreement with Bohr's straggling theory except in the case of the Σ^-, where theory predicts 10 μ and we observe 1.5 μ.

The pion ranges were measured independently by two observers with an automated coordinate readout microscope. Some ranges were also measured graphically by plotting the grid coordinates (a 1-mm grid is photographed on each pellicle) of the pion track. The two methods of measurement agreed within 1% for each track. The baryon ranges were measured in accord with our previously established[6] standards. The data from all stacks are consistent. By careful measurements, the collinearity of tracks from processes (3) and (4) also was tested. There is, in any case, no possibility of mistaking K^- capture by a bound proton for one by a free proton because of the large difference in Q values.

The low-velocity ($\beta < 0.28$) portion of the proton RE relation has been much studied, and in connection with the present program was rechecked. There is less empirical data on which to base the high-velocity range table needed for the pions. The original tables[4,6] were calculated from theory using a mean excitation potential, I, of 331 eV and the shell corrections calculated by Walske.[7] Later high-velocity data by Barkas and von Friesen[8] gave a range of I values from 304 to 328 eV, and other information cited by them indicated that 331 eV might by somewhat high. In the meantime range tables with more elaborate shell corrections at a series of I values were prepared.[9] These tables and the measurements of Table I now enable us to improve our estimate of the emulsion I value.

Reaction (1) uses only the well-established portion of the range-energy curve. From it we obtain for the mass of the Σ^+ hyperon 1189.36 ± 0.17 MeV. In order to obtain the same Σ^+ mass from Reaction (2) as from Reaction (1), we assume that I is an adjustable parameter. To obtain agreement between Reactions (1) and (2) we must take $I = 319 \pm 9$ eV. We also require momentum balance between the hyperon and pion in Reaction (3). To bring the pion momentum into agreement with that deduced from the Σ^+ range and mass, we must choose $I = 329 \pm 20$ eV. The best estimate is therefore $I = 321 \pm 8$ eV. It is notable that raising the I value raises the calculated mass from Reaction (2) and lowers it in Reaction (3).

In what follows we used the existing[4,5] RE tables for $\beta < 0.28$, and for high velocities use the new table of reference 9 with $I = 320$ eV. They agree at $\beta = 0.28$. We estimate the uncertainty of the tabulated ranges at high velocities to be $\pm\frac{1}{2}$%.

Derived masses.—We combine the Σ^+ mass estimate from Reaction (2) [which is partially dependent on Reaction (1)] with the value from Reaction (1) to obtain a best estimate of the Σ^+ mass. It is 1189.35 ± 0.15 MeV. The K^- mass is best obtained from the Σ^+ range in process (3). For it we find 493.7 ± 0.3 MeV.

The Σ^- hyperon mass is now determined from the pion ranges of Reactions (3) and (4) and the mass of the Σ^+. We find

$$M_{\Sigma^-} = [2(M_p + M_K)(T_{\pi^-} - T_{\pi^+}) + M_{\Sigma^+}{}^2]^{1/2}$$

$$= 1197.6 \pm 0.5 \text{ MeV}.$$

The error includes the uncertainties in the Σ^+ and K^- masses, and the uncertainty in the pion energy difference $(T_{\pi^-} - T_{\pi^+})$. The Σ^- mass is insensitive to the RE relation and to the K^- mass.

This result changes substantially our mass estimate for the Σ^- hyperon and also that for the Σ^0, which is tied to it. (The new value for Σ^0 is 1193.2 ± 0.7 MeV.) In a recent tabulation[10] of particle masses a footnote reference to the anomaly was made, but the Σ^- mass was derived using its own range in Reaction (4).

The energy-loss defect of the negative hyperon.– The momentum of the pion in Reaction (4) is 172.74 ± 0.38 MeV/c. Were the stopping cross sections of positive and negative particles equal, a Σ^- hyperon with this momentum and the above mass would have a range of 684 ± 5 μ. We observe 708.9 ± 1.5 μ.

It is well known that stopping theory based on the first Born approximation fails when the particle velocity becomes comparable to the velocities of many of the electrons in the stopping material. It is perhaps not surprising that there should appear a small difference between the stopping cross sections of positive and negative particles in this region, because their predicted equality is also a first Born approximation result, while a difference exists in the second approximation. At high velocities this effect is not expected. At intermediate velocities it is interesting to note that this effect probably is the explanation for an apparent difference between the positive and negative pion masses, which has remained unexplained for many years.[11,12] We know of no other measurements of sufficient accuracy for the effect to have been observed before. A quantitative estimation of the effect is being attempted.

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