[8]One may argue that this ratio could be incorrect inasmuch as events in the $\Xi^*(1530)$ overlap region of Fig. 1(b) have been included as well as events that fall in the $K^*(890)$ region of Fig. 2(a). Subtracting these events, we obtain a ratio of 0.4 ± 0.3.

[9]Identification of the $\Lambda\bar{K}$ decay mode as discussed in reference 7 provides a confirmation of this isospin assignment.

[10]The $\frac{3}{2}^+$ assignment for the $\Xi^*(1530)$ is also favored, based on an analysis of $\Xi^*(1530)$ decay by one of us (J. B.-S.). In the following arguments, we assume that the Λ^0 and Ξ are $\frac{1}{2}^+$; the π and K are 0^-.

[11]The angular-momentum and phase-space dependence of the decay rate may be expressed in the form

$$\Gamma\propto|(p^2+X^2)^2|^l(p/m),$$

where p is the momentum of decay products of a resonance of mass M, and X, which is related to the size of the interaction, is adjusted to a size of interaction equal to $\hbar/2m_\pi$. The momenta for $\Xi^*\pi$, $\Lambda\bar{K}$, and $\Xi\pi$ are 230, 390, and 410 MeV/c respectively.

[12]A. Halsteinslid, R. Møllerud, J. M. Olsen, H. H. Bingham, H. Bermeister, D. C. Cundy, G. Myatt, M. Paty, O. Skjeggestad, P. Belliere, V. Brisson, P. Petiau, A. Rousset, C. M. Fisher, J. M. Scarr, F. W. Bullock, and B. S. Luetchford, Proceedings of the Sienna International Conference on Elementary Particles (Società Italiana di Fisica, Bologna, Italy, 1963).

NEW DETERMINATION OF THE MASSES OF Σ^- AND Σ^0 HYPERONS*

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The low energy K^- beam[1] at the CERN proton synchrotron stopping in the 81-cm Saclay hydrogen bubble chamber[2] yielded many examples of the following at-rest reactions:

$$K^-+p\rightarrow\Sigma^-+\pi^+, \tag{1}$$

$$\Sigma^-+p\rightarrow\Lambda+n, \tag{2}$$

$$\Sigma^-+p\rightarrow\Sigma^0+n$$
$$\quad\llcorner\!\rightarrow\Lambda+e^++e^-. \tag{3}$$

In this note, the mass of the Σ^- hyperon is determined in terms of the better known masses[3] of the other particles in reactions (1) and (2), by measuring the momentum from the range of stopping Σ^- in (1) and from the momentum of the Λ in reaction (2). The (Σ^-, Σ^0) mass difference is determined from the value of the Σ^0 momentum in reaction (3).

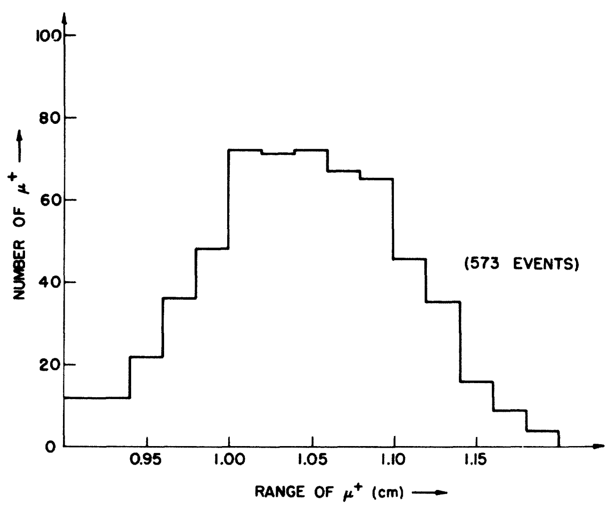

FIG. 1. Observed range distribution of μ^+ from π^+-μ^+ decays at rest.

A significant experimental error in the Σ^- mass determination arises from the uncertainty of the density of hydrogen in the bubble chamber. The hydrogen density was found by measuring the ranges of a sample of 573 stopping μ^+ from stopping π^+. The mean range of the μ^+ is 1.049 ± 0.0035 cm (statistical errors only), and corresponds to a hydrogen scale factor of 1.068 ± 0.0035.[4] Figure 1 shows the μ^+ range distribution. As a further check, we looked at a sample of 400 stopping protons which came from Λ's directly produced from stopping Σ^- via Reaction (2). Using the known mass of the Λ, but treating the Λ momentum and the proton momentum as unknown, we determined the best value for the proton momentum from a two-constraint fit to the Λ decay hypothesis. Comparison of this deduced proton momentum with the measured length of each proton, via the range-momentum table, led to a value of the hydrogen scale factor of 1.068 ± 0.008, in excellent agreement with the value deduced from $\pi^+\rightarrow\mu^+$ decays. In the analysis that follows we adopt a scale factor of 1.068 ± 0.005.[5]

In addition to the density, the magnetic field in the chamber must be known to a reasonable accuracy.[6] The shape of the magnetic field was determined by a careful mapping over the volume of the chamber at CERN. Using this shape, the absolute magnetic field was determined to better than ±0.5% by measuring the momenta of the π^- from a sample of at-rest reactions of the type $K^- + p \rightarrow \Sigma^+ + \pi^-$. A comparison of the mean value of the π^- momentum with the value of 181.47 MeV/c deduced from the known masses involved in this reaction served to fix the magnetic field to better than ±0.5%. (The mean π^- momentum is obtained after correcting each measurement for the fact that inverse projected curvature, not momentum, is expected to be Gaussian distributed.)

(a) Σ^- mass from range. —A sample of 588 Σ^- hyperons produced from at-rest (K^-,p) reactions of type (1), with lengths between 0.95 and 1.15 cm, was used. The Σ^- range distribution is displayed in Fig. 2. The mean Σ^- range in the stopping peak is 1.050 ± 0.0015 cm (using a Gaussian ideogram plot).

The mean measured range of Σ^- from Reaction (1) implies a Σ^- mass of 1196.9 ± 0.30 MeV, adopting 493.9 MeV as the K^- mass[3] and a hydrogen density uncertainty of ±0.5%. If the 0.2-MeV uncertainty in the K^- mass[3] is included, the value of the Σ^- mass becomes 1196.9 ± 0.36 MeV.

(b) Σ^- - Λ mass difference from direct Λ momentum. —From the above sample of 588 stopping Σ^- from Reaction (1), we have found 285 Λ's from Reaction (2). These Λ's were selected by the requirement that the Λ kinetic energy fall between 34.35 and 39.35 MeV. The Λ momentum was deduced from the (3C) fit of the p, π^- measured variables, using the Λ mass of 1115.36 MeV.[3] These events are displayed in Fig. 3. The mean direct Λ momentum was 289.3 ± 0.16 MeV/c (using a Gaussian ideogram plot).[6] This implies a Σ^- - Λ mass difference of 81.7 ± 0.19 MeV, including a ±0.5% error in the hydrogen density and a small error due to the magnetic field uncertainty.[6] The Σ^- mass is then determined to be 1197.0 ± 0.24 MeV when the error of ±0.14 MeV in the Λ mass is included.

The Σ^- mass values deduced by methods (a) and (b) are in excellent agreement with each other. A combination of the three measurements—the μ^+ range, the Σ^- range, and the Λ momentum—can be used to give the best estimate of the Σ^- mass as is shown in Fig. 4. As deduced from range, the Σ^- mass shows a different variation with hydrogen density than the Σ^- mass as deduced from direct Λ momentum. The error bands for the Σ^- mass from (a) and (b) include the K^- mass and Λ mass uncertainties, respectively. The best value of the Σ^- mass from Fig. 4, including all errors, is

$$M_{\Sigma^-} = 1197.0 \pm 0.20 \text{ MeV}.$$

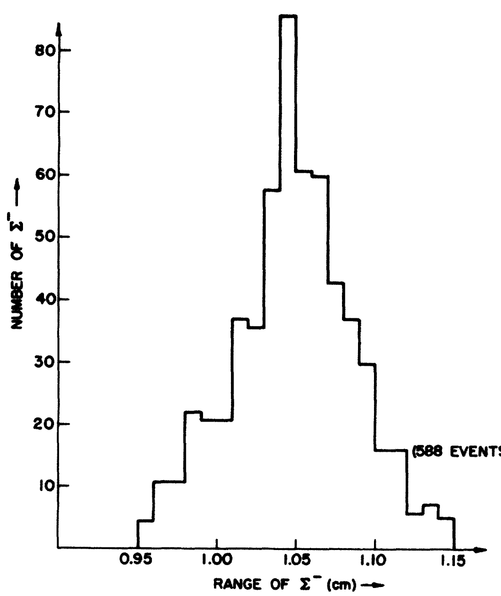

FIG. 2. Observed range distribution of Σ^- from at-rest reaction $K^- + p \rightarrow \Sigma^- + \pi^+$.

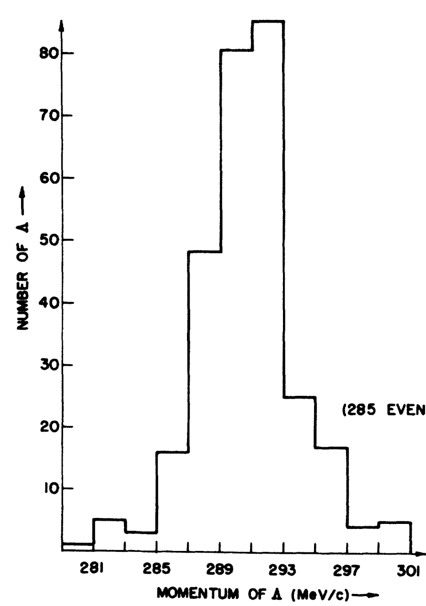

FIG. 3. Observed momentum distribution for directly produced Λ from the at-rest reaction $\Sigma^- + p \rightarrow \Lambda + n$.

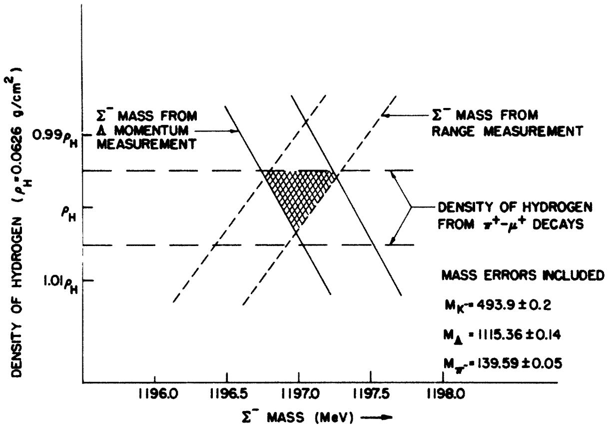

FIG. 4. Σ^- mass from range, momentum, and density of hydrogen measurements, as explained in the text.

This result can be compared with the recent measurement of Barkas, Dyer, and Heckman[7] of 1197.6±0.5 MeV using nuclear emulsions.

We have made one further over-all check on our results by measuring 20 events of the type

$$K^- + p \rightarrow \Sigma^+ + \pi^- \ (K^- \text{ at rest}), \tag{4}$$

$$\Sigma^+ \rightarrow p + \pi^0 \ (\Sigma^+ \text{ at rest}). \tag{5}$$

These events were from a sample of ~4000 Σ^+ produced by stopping K^- mesons. Events were retained in the final sample if the chi-squares for Reaction (4) were satisfactory and if the range of the Σ^+ produced in Reaction (4) was between 1.16 and 1.36 cm, and the range of the decay proton was in the interval 2.43 to 3.08 cm.

The mean range of the Σ^+ (1.254±0.011), together with the mean range of the proton (2.748 ±0.027) from the $\Sigma^+ \rightarrow p + \pi^0$ decay at rest, determines both the Σ^+ mass and the density of hydrogen in the bubble chamber. A plot similar to Fig. 4, exhibiting the interdependence of hydrogen density, the Σ^+ mass as determined from the Σ^+ range, and the proton range, gives a Σ^+ mass of 1189.5±0.5 MeV. (This measurement agrees with the emulsion value of 1189.4±0.2 MeV.) At the same time the scale factor for the density of hydrogen in the bubble chamber is determined to be 1.068±0.010, which agrees well with our other measurements of this quantity.

(c) Σ^-, Σ^0 mass difference. —A very accurate (Σ^-, Σ^0) mass difference can be determined from a measurement of Σ^0 momenta from the at-rest reaction $\Sigma^- + p \rightarrow \Sigma^0 + n$. The Σ^0 momentum can be directly determined from the rare mode of decay (~1/180), $\Sigma^0 \rightarrow \Lambda + e^- + e^+$, where the Λ decays into $p + \pi^-$. This sequence occurs about once in every 5000 reactions of type (1).

We have measured 18 of these events, where the Σ^- length is between 0.95 and 1.15 cm and where the Σ^0 momentum is between 50 and 70 MeV/c. The momentum of the Σ^0 is determined from the vector sum of the measured momenta of the Dalitz-pair electrons and the fitted Λ momentum. The weighted average of these Σ^0 momenta is 60.3±0.9 MeV/c.[6] This implies[8] a $\Sigma^- - \Sigma^0$ mass difference of 4.75±0.10 MeV. This agrees with the previous value 4.45±0.4 MeV.[3] Combining this result with our value, $M_{\Sigma^-} = 1197.0 \pm 0.20$ MeV, we get $M_{\Sigma^0} = 1192.25 \pm 0.23$ MeV.

Summarizing, by assuming the masses $M_{K^-} = 493.9 \pm 0.2$, and $M_\Lambda = 1115.36 \pm 0.14$, we have deduced the masses

$$M_{\Sigma^-} = 1197.0 \pm 0.20 \text{ MeV}$$

and

$$M_{\Sigma^0} = 1192.25 \pm 0.23 \text{ MeV}.$$

Using $M_{\Sigma^+} = 1189.4 \pm 0.2$ MeV, we see that

$$M_{\Sigma^-} - M_{\Sigma^0} = 4.75 \pm 0.10 \text{ MeV},$$

while

$$M_{\Sigma^0} - M_{\Sigma^+} = 2.85 \pm 0.30 \text{ MeV},$$

so that the prediction[9] of equal spacing within the Σ multiplet is approximately, but apparently not exactly, satisfied. The observed deviation from even spacing is in the same direction as that calculated by Coleman and Schnitzer[10] from the "leading nontadpole contributions to electromagnetic mass splittings." Their results for the Σ multiplet are $M_{\Sigma^-} - M_{\Sigma^0} = 5.8$ MeV and $M_{\Sigma^0} - M_{\Sigma^+} = 3.8$ MeV with a theoretical uncertainty of the same order as the difference between theory and this experiment, namely 1 MeV.

The work could not have been begun without the contributions of our collaborators in other aspects of this CERN stopping K^- experiment, particularly H. Courant, H. Filthuth, A. Segar, and W. Willis. We are indebted to the crews of the CERN proton synchrotron and the Saclay 81-cm chamber for their unflagging cooperation, and to the scanners of the University of Maryland for their perserverance and perspicacity.

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and W. Willis, Proceedings of the International Conference on Instrumentation for High-Energy Physics at CERN (North-Holland Publishing Company, Amsterdam, 1963).

[2]P. Baillon, thesis, University of Paris, 1963 (unpublished).

[3]W. Barkas and A. Rosenfeld, University of California Radiation Laboratory Report No. UCRL 8030, September 1960 (unpublished).

[4]This scale factor is the one used in the Berkeley range-momentum table. See A. H. Rosenfeld, University of California Radiation Laboratory Report No. UCRL 9099 (unpublished).

[5]The error on the scale factor has been increased slightly to include an uncertainty in the ionization potential of hydrogen, which contributes about 0.2% uncertainty in the range-energy relationship (see reference 4) and other possible systematic errors estimated at 0.3%.

[6]An error of ±0.5% in the field contributes an error of approximately 0.05% and 0.3% in the Λ and Σ^0 momenta, respectively.

[7]W. H. Barkas, J. T. Dyer, and H. H. Heckman, Phys. Rev. Letters 11, 26 (1963). The physical effect noted here, that slow negative hyperons lose energy at a lower rate than slow positive particles of the same velocity due to the breakdown of the first-order Born approximation, is expected to play a negligible role in liquid hydrogen as contrasted to nuclear emulsion. The effect can only be significant when the velocity of the moving particle becomes comparable to the velocity of the electron in the medium. In liquid hydrogen this occurs at a velocity of the Σ^- such that its residual range is negligible. Hence the Born-approximation range-momentum relation calibrated with positive μ^+ and protons should be valid for Σ^-.

[8]The Σ^--Σ^0 mass difference is given to good approximation by $M_{\Sigma^-}-M_{\Sigma^0}=(1.30+0.9465\times10^{-3}p_{\Sigma^0}^{\;2})$ MeV, where p_{Σ^0} is in MeV/c.

[9]S. Coleman and S. L. Glashow, Phys. Rev. 134, B671 (1964); and earlier references contained therein.

[10]S. Coleman and H. J. Schnitzer, to be published.

K^-p CHARGE EXCHANGE AT 2.00 BeV/c

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The differential cross section for the reaction

$$K^-+p\to\bar{K}^0+n$$

has been measured for (2.00 ± 0.020)-BeV/c K^- in the Brookhaven 20-in. bubble chamber using the separated K^- beam from the AGS.

A total of about 100 000 pictures were taken, having an average flux of 6.21 tracks per picture and a purity of 100% with a statistical accuracy of 9.6%, as estimated from the number of τ decays found in about 40% of the pictures.

The events appear as beam tracks that interact in flight producing no visible outgoing prongs, followed by decay of the $\bar{K}_1^0$ into two charged particles. The value of the charge-exchange cross section was estimated in the following way: From all the pictures 88 events were identified as $\bar{K}^0N$. Identification was based on kinematics