Mass of the Charged Σ Hyperons*

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Twenty-nine examples of Σ^+ hyperon decays at rest into protons were used to determine the mass of the Σ^+ hyperon. The stopping power for each batch of emulsions containing these events was determined by making use of μ^+-meson ranges obtained from the decay of π^+-mesons at rest. The mean range of protons from Σ^+ decays was found to be 1686.5±6.0 microns. The rms deviation was 37.2±6.0 microns. The Q value for the decay ($\Sigma^+ \rightarrow p+\pi^0$) was found to be 116.37±0.4 Mev and the mass of the Σ^+ hyperon, $(2328.1 \pm 0.8)m_e$. An analysis of three collinear events, which resulted from the interaction of stopped K^- mesons with hydrogen nuclei of the emulsion, gave the Σ^- hyperon mass to be $(2341.6\pm 2.0)m_e$ and the mass difference between Σ^- and Σ^+ hyperons $(13.5\pm 2.0)m_e$.

INTRODUCTION

THE following decay schemes for the decay of the Σ^+ hyperon,

$$\Sigma^+ \rightarrow p+\pi^0+116 \text{ Mev}, \quad (1)$$

$$\Sigma^+ \rightarrow n+\pi^+ +110 \text{ Mev} \quad (2)$$

are well established. Since the energy of the proton from the Σ^+ decay at rest in Eq. (1) is about 18 Mev, it is clear that the mass of the Σ^+ hyperon could be determined with considerable precision from a small sample of decays. A precise measurement of the Σ^+ mass was made by Fry *et al.*[1] and by Barkas *et al.*[2] using the decay scheme given by Eq. (1). In the work presented here a sample of 29 protonic decays of Σ^+ hyperons at rest was selected for the re-determination of the Σ^+ mass. The events in (1) are also included in this work.

The range straggling of protons and variations in the stopping power and shrinkage factors of different emulsion batches are the main factors that set a limit on the accuracy of the mass measurement. For this reason it is necessary to determine the shrinkage factor and stopping power for each batch of emulsion with considerable precision. In order to keep the errors in the mass measurement to a minimum it is essential to have the error in the proton energy, due to uncertainty in the stopping power and shrinkage factor, less than the error introduced by the range straggling of protons.

The mass of the Σ^- hyperon cannot be determined with considerable precision from its decay products, for a Σ^- hyperon either decays in flight into a π meson or interacts from rest with a nucleus of the emulsion giving rise to an evaporation star. However, the Σ^- mass can be determined accurately by utilizing the following K^- reactions together:

$$K^- + p \rightarrow \Sigma^+ + \pi^- + Q_3, \quad (3)$$

$$K^- + p \rightarrow \Sigma^- + \pi^+ + Q_4. \quad (4)$$

Two possible procedures exist for determining the Σ^- mass using the above reactions:

(i) Knowing the mass of the Σ^+ hyperon, the mass of the K^- meson can be determined using the reaction (3). Then the Σ^- mass can be computed from reaction (4).

(ii) The reactions (3) and (4) lead to the relation $M_{\Sigma^-} - M_{\Sigma^+} = Q_3 - Q_4$, and if the values of Q_3 and Q_4 are measured, it gives the mass difference between the Σ^- and Σ^+ hyperons. Here an iteration method can be used to estimate the mass difference. In this method it is first assumed that the Σ^- mass is equal to that of the Σ^+ and the value of Q_4 is determined. This value of Q_4 is used to calculate the mass difference, which in turn gives the Σ^- mass. This procedure is repeated using the new Σ^- mass value until the Σ^- mass no longer alters the value of Q_4.

MASS OF THE Σ^+ HYPERON

Procedure.—A sample of twenty-nine Σ^+ decays from rest into protons, obtained in plates exposed to particles from the Cosmotron and Bevatron accelerators was chosen for the mass determination. The regression method[3] was used to determine the shrinkage factor and stopping power for each batch of emulsions. This was done using the measured ranges of μ-mesons resulting from the decay of positive pions at rest. The expected range straggling of the protons from the Σ^+ decays from rest is about 25 microns (i.e., 1.5%) and hence it is necessary to know the stopping power for each batch with an accuracy of at least 0.5%. The straggling of μ-mesons from π-μ decays has previously been found to be 29.1±0.7 microns by Fry and White[3] and 27.1±0.8 microns by Barkas.[4] Thus to obtain an

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[1] Fry, Schneps, Snow, and Swami, Phys. Rev. **103**, 226 (1956).
[2] Barkas, Giles, Heckman, Inman, Mason, and Smith, University of California Radiation Laboratory Report UCRL-3892 (unpublished).
[3] W. F. Fry and G. R. White, Phys. Rev. **90**, 207 (1953).
[4] Barkas, Smith, and Birnbaum, Phys. Rev. **98**, 605 (1955).

TABLE I. Summary of μ-meson range measurements.

Exposure	Mean range in microns	Variance	Shrinkage factor
K^-	599.1±2.1	30.1±2.1	2.58
3-Bev π^-	588.9±2.2	31.4±2.2	2.40
3-Bev p	611.0±2.4	35.4±2.4	2.58
K^- (Stack 3)	599.2±2.2	29.2±2.2	2.48
K^- (Stack 4)	598.0±2.0	27.0±2.0	2.39

accuracy of 0.5% in the mean range of μ-mesons, it was necessary to have a sample of 100 π-μ decays for measurement.

The energy of the protons was determined from their mean range using the range-energy relationship of Barkas.[5] The mean range of μ-mesons from π-μ decays in the emulsion of the density used by Barkas was 602 microns. The range of each proton from a Σ^+ decay was corrected for variation in the stopping power by multiplying it by the ratio of the mean range of the μ-mesons from π-μ decays (in the same emulsion batch) to the range 602 microns. The mean energy of the protons was then found from the mean of the corrected ranges. The energy of the π^0-mesons was determined by the requirement that momentum be balanced between the proton and the π^0-meson. The energy release from the Σ^+ decay and the mass of the Σ^+ hyperon were then determined by assuming the decay scheme $\Sigma^+ \rightarrow p+\pi^0$ and using the known masses of the proton and the π^0-meson.

Experimental results.—Of the twenty-nine Σ^+ decays from rest into a proton, twenty-four were produced by the absorption of stopped negative K mesons, three by 3-Bev π^--mesons, and two by 3-Bev protons.

The mean range of μ^+-mesons from π-μ decays was determined for each pellicle stack and the details of the measurements are given in Table I. The best value for the variance of the μ-meson range distribution is 30.6±1.0 microns which is consistent with previously measured values.

The following are the main sources of error in measuring the proton ranges: (i) inaccuracy in stepping off the segments, (ii) distortion of the emulsion, and (iii) errors due to "following through" at the surfaces of the adjacent pellicles. These sources of error were taken into consideration in measuring the ranges of the protons. The mean range of the protons from the 29 Σ^+ decays was 1686.5±6.0 microns. The root-mean-square deviation was 37.2±6.0 microns.

It is to be noted here that the ranges of protons from Σ^+ decays in different emulsion batches are consistent with a single distribution only after correction for the stopping power. The range frequency histogram for the protons is given in Fig. 1 and the smooth curve represents the normalized Gaussian distribution fit for the histogram. This distribution is consistent with the assumption that the protons from Σ^+ decays are monoenergetic.

The energy of a proton of mean range 1686.5±6.0 microns is 18.91±0.1 Mev. The error in the energy not only represents the error due to straggling but also the error in the range energy relationship which is 0.7% in range when the stopping power is accurately known. With this energy for the proton, the energy the π^0-meson must have for momentum balance is 97.7±0.4 Mev. Using the known mass of the proton $(1836.12 \pm 0.02)m_e$,[6] and that of the π^0-meson, $(264.27\pm 0.32)m_e$,[6] the Q value for the decay scheme $\Sigma^+ \rightarrow p+\pi^0$ is found to be 116.37±0.4 Mev and the mass of the Σ^+ hyperon is $(2328.1\pm 0.8)m_e$. The error arising due to uncertainty in the π^0-meson mass was taken into account in computing the errors in the Q value and the Σ^+ mass.

MASS OF THE Σ^- HYPERON

Procedure and results.—In a systematic survey of 1001 stars produced by stopped K^- mesons, three events were observed which were interpreted as captures from rest of K^- mesons by protons. The Σ hyperon and the π meson produced in each of the three events were collinear within errors of measurement. The observed collinearity is strong evidence for interpreting these events as captures in hydrogen. A summary of the measurements is given in Table II.

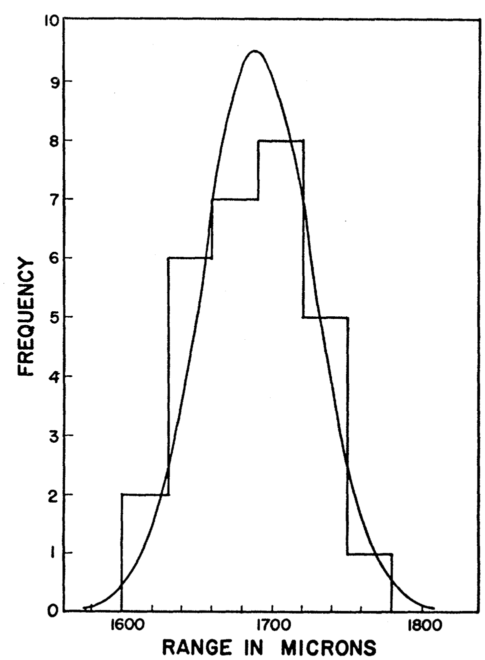

FIG. 1. Range frequency histogram of protons from Σ^+ decays at rest. The curve represents the normalized Gaussian fit for the histogram.

[5] W. H. Barkas, University of California Radiation Laboratory Report UCRL-3769, 1957 (unpublished).

[6] Cohen, Crowe, and DuMond, *Fundamental Constants of Physics*, Interscience Monographs in Physics and Astronomy (Interscience Publishers, New York, 1957), Vol. 1, Chap. 4, p. 47.

TABLE II. Characteristics of K^--hydrogen events.

Event	Reaction	Range of the hyperon in microns	Energy of the hyperon in Mev	Energy of the π-meson in Mev	Q value in Mev	Dip angle of the hyperon in degrees	Angle between π-meson and the hyperon in degrees
1	$K^-+p\rightarrow\Sigma^++\pi^-$	828.0±13	13.82±0.14	88.66±0.74	102.48±0.75	5	180.0±0.5
2	$K^-+p\rightarrow\Sigma^-+\pi^+$	694.2±11	12.51±0.12	83.08±0.60	95.59±0.61	37	180.0±0.5
3	$K^-+p\rightarrow\Sigma^-+\pi^+$	694.9±11	12.51±0.12	83.08±0.60	95.59±0.61	0	180.0±0.4

It is worthwhile to point out that these events are undoubtedly not captures in heavy elements of the emulsion with invisible recoils, because the chance of observing such collinear events is small. Out of a total 1001 K^- stars observed, 44 consist of only a meson and a hyperon.[7] The probability that the Σ hyperon and the π meson from such a star are collinear within 1° is 2.5×10^{-4}, assuming that the hyperon is distributed uniformly over a solid angle of π steradians. In addition another factor which reduces the probability of our observed events being accidental is the fact that the energy of a Σ hyperon emitted in a nonhydrogen capture will be substantially different from the observed energies.

The shrinkage factors and the stopping powers of the emulsions containing these events are known accurately and the error estimates made here are similar to the errors estimated in determining the mass of the Σ^+ hyperon.

Some of the events presented here had been described elsewhere[8] but have been remeasured and, therefore, only the essential details will be presented. In event 1, the range of the proton (1635±26 microns) is strong evidence that the Σ^+ hyperon decayed from rest. Since the mass of the Σ^+ hyperon has been determined with considerable accuracy, the mass of the K^- meson can be computed from reaction (3). Taking the masses of the Σ^+ hyperon and the π^- meson to be $(2328.1\pm0.8)m_e$ and $273.3\pm0.2)m_e$, respectively and using the range energy relationship of Barkas,[5] the mass of the K^- meson is found to be $(965.8\pm1.5)m_e$.

[7] Fry, Schneps, Snow, Swami, and Wold, Phys. Rev. **107**, 257 (1957).

[8] Fry, Schneps, Snow, Swami, and Wold, Phys. Rev. **104**, 270 (1956).

In event 2 the Σ^- hyperon does not produce a visible star at the end of its range but there appears to be a low-energy electron associated with its end suggesting the capture of a negative particle. The Σ^- hyperon from event 3 has a low-energy electron and a 5-mm long singly charged particle associated with its end. In order to determine the mass, a self-consistent procedure was adopted. The Σ^- mass was made a variable parameter in reaction (4) and the mass of the K^- meson was determined. The parameter was varied in small steps and the value of it which gave the correct mass of the K^- meson as determined from reaction (3) was adopted as the mass of the Σ^- hyperon. The mass of the Σ^-, using method (i), was found to be $(2342.0\pm2.0)m_e$ and the mass difference was $(13.9\pm2.0)m_e$. The mass difference between the Σ^- and Σ^+, using method (ii), was found to be $M_{\Sigma^-}-M_{\Sigma^+}=Q_3-Q_4=(13.5\pm2.0)m_e$ and the mass of the Σ^- would then be $(2341.6\pm2.0)m_e$. This determination of mass difference is independent of the exact knowledge of the stopping power of the emulsion and of the absolute K^- mass value.

The above mass difference is in excellent agreement with the value $(12.3\pm1.3)m_e$ given by Barkas *et al.*[2]

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