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Mass of the Σ^+ Hyperon*

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Ten examples of the protonic decay from rest of the Σ^+ hyperon have been analyzed. The ranges of the protons from the Σ^+ decays were corrected for variations in the stopping power of each emulsion batch by determining the mean range of μ mesons from $\pi-\mu$ decays. The mean range of the protons, after correcting for variations in stopping power, was found to be 1669.4±8.0 microns. The rms deviation of the proton ranges was found to be 38.5±8.0 microns. The Q of the Σ^+ decay, $\Sigma^+\rightarrow p+\pi^0$ is 116.1±0.5 Mev, and the mass of the Σ^+ hyperon is $(2327.4\pm1.0)m_e$.

I. INTRODUCTION

The first few examples[1] of the decay from rest of the charged Σ^+ hyperon into a proton strongly suggested that only two particles are involved in the decay. The ranges of the protons were nearly the same and the small differences could be attributed to straggling and to variations in the stopping power of the emulsion. The consistency with the charged mesonic decay mode[2] strongly suggests that the neutral particle associated with the protonic decay is the π^0 meson. It was immediately recognized that the mass of the Σ^+ hyperon could be determined with considerable precision from a very few events.[3] The limitations in the measurements are principally the result of the range straggling of the protons, which is quite small, and variations in the stopping power of the emulsion. It is known that the stopping power of emulsion varies from one batch to another due to variations in the water content[4] and probably to small changes in the chemical composition. For this reason it is necessary to determine the stopping power and shrinkage factor for each batch with considerable precision. It is desirable to have the error in the proton energy due to the uncertainty in the stopping power less than the error introduced by the range straggling of the protons for the sample to be studied.

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[1] Bonetti, Levi Setti, Panetti, and Tomasini, Nuovo cimento **10**, 1736 (1953); Castagnoli, Cortini, and Manfredini, Nuovo cimento **12**, 464 (1954); Baldo, Belliboni, Ceccarelli, and Vitale, Nuovo cimento **12**, Suppl. 2, 289 (1954); W. F. Fry and M. S. Swami, Phys. Rev. **96**, 235 (1954).

[2] Bonetti, Levi Setti, Panetti, and Tomasini, Nuovo cimento **10**, 345 (1953); Lal, Pal, and Peters, Bagneres Conference Report 146, 1953 (unpublished); King, Seeman, and Shapiro, Phys. Rev. **92**, 838 (1953); M. Ceccarelli and M. Merlin, Nuovo cimento **10**, 1207 (1953); York, Leighton, and Bjørnerud, Phys. Rev. **95**, 159 (1954); M. W. Friedlander, Phil. Mag. **45**, 418 (1954).

[3] The papers listed in reference 1 report the following Q values, respectively (in Mev): 115±3, 117±1.3, 116.0±2.0, 117±2.

[4] A. J. Oliver, Rev. Sci. Instr. **25**, 326 (1954). According to J. Rotblat [Nature **167**, 550 (1951)], we would expect that the variation of the stopping power within a given batch of emulsion is negligible.

II. PROCEDURE

Twelve examples of the protonic decay from rest of a Σ^+ hyperon were found in plates exposed to particles from the Cosmotron and Bevatron accelerators. Two of these twelve were not suitable for precise measurements and were not used in the mass determination. The stopping power of each batch of emulsion has been determined by measuring the range of μ mesons from $\pi-\mu$ decays. The regression method[5] was used to determine the shrinkage factor for each batch. The expected straggling of the protons from decays from rest is[6] about 25 microns $[(25/1670)\times100=1.5\%]$, and hence for a sample of ten Σ^+ decays it is necessary to know the stopping power of each batch with an accuracy of at least 0.6%. The straggling of μ mesons from $\pi-\mu$ decays has previously been found to be 29.1±0.7 by Fry and White[5] (probable error in straggling) and 27.1±0.8 microns by Barkas.[6] Therefore, in order to determine the mean range of the μ mesons with a precision of 0.6%, it is necessary to have a sample of about $[(29/600)(100/0.6)]^2\cong70$ $\pi-\mu$ decays. It was decided to measure the range of 100μ mesons from $\pi-\mu$ decays in each batch of emulsion containing Σ^+ hyperon decays.

The energy of the protons was determined from their mean range using the range-energy relationship of Barkas.[7] The mean range of μ mesons from $\pi-\mu$ decays in emulsion of the density used by Barkas in the range-energy measurements is 602 microns. The range of each

Table I. Summary of μ-meson range measurements.

Exposure	Mean range in microns	Variance	Shrinkage factor	δ[a]
K^-	599.1±2.1	30.1±2.1	2.58	0.13
3-Bev π^-	588.9±2.2	31.4±2.2	2.40	0.20
3-Bev p	611.0±2.4	35.4±2.4	2.58	−0.06

[a] δ is the correction to the originally assumed shrinkage factor. The value for δ was found by the regression method.[5]

[5] W. F. Fry and G. R. White, Phys. Rev. **90**, 207 (1953).

[6] Barkas, Smith, and Birnbaum, Phys. Rev. **98**, 605 (1955).

[7] Bradner, Smith, Barkas, and Bishop, Phys. Rev. **77**, 462 (1950). W. H. Barkas and H. Hahn, University of California Radiation Laboratory Report UCRL-2579 (unpublished). The authors are indebted to Dr. Barkas for several informative discussions relating to the range-energy relationship.

proton from a Σ^+ decay was corrected for variation in stopping power by multiplying it by the ratio of the mean range of the μ mesons from $\pi-\mu$ decays (in the same batch of emulsion) to the range 602 microns. The mean energy of the protons was then found from the mean of the corrected ranges.

The energy release from the Σ^+ decay and the mass of the Σ^+ hyperon were determined by assuming the decay scheme $\Sigma^+ \rightarrow p+\pi^0$ and using the known masses of the proton and π^0 meson.

III. EXPERIMENTAL RESULTS

Of the twelve Σ^+ hyperons which decayed from rest into a proton, six were produced by the absorption of stopped negative K mesons, three by 3-Bev π^- mesons, one by a 4-Bev π^- meson, and two by 3-Bev protons.

The mean range of μ mesons from $\pi-\mu$ decays was determined in the pellicle stacks exposed to stopped K^- mesons, to 3-Bev π^- mesons, and to 3-Bev protons.

TABLE II. Characteristics of Σ^+ hyperons.

Event	Source	Length of track (microns)
1	3-Bev π^-	>1500
2	3-Bev π^-	> 800
3	3-Bev π^-	40
4	K^-	250
5	K^-	290
6	K^-	920
7	K^-	1560
8	K^-	302
9	3-Bev p	264
10	3-Bev p	820
11	4-Bev π^-	275
12	K^-	227

The data on the μ-meson range measurements are given in Table I.

The best value for the variance of the μ-meson range distribution from this work is 32.3±1.4 microns which is consistent with previously measured values.

The origins of the Σ^+ hyperons and the lengths of their tracks are given in Table II.

A summary of the measurements of the ranges of the protons from the Σ^+ decays is given in Table III.

The estimated error in the measurement of the range of the proton from the Σ^+ decays (column 3 in Table III) is based on several contributing factors; namely, inaccuracies in stepping off segments of the track, distortion, and errors due to "following through" at the surfaces of adjacent pellicles. The error introduced by the uncertainty in the stopping power is included in the error of the range corrected for stopping power (column 4 in Table III).

The mean range of the protons from events 1 through 10 is 1669.4±8.0 microns. The root-mean-square deviation of the proton ranges is 38.5±8.0 microns. This variance is to be compared with a straggling of 25 microns predicted by Barkas.[6]

TABLE III. Measurements of proton ranges from Σ^+ decays.

Event	Measured range of proton in microns[a]	Estimated error in range measurement[b] (microns)	Range corrected for stopping power (microns)	Average dip angle of proton in degrees	Number of plates containing proton track
1	1583	15	1619±17	13	2
2	1626	10	1663±13	13	1
3	1591	25	1626±26	35	3
4	1718	26	1725±27	40	3
5	1725	26	1734±27	38	3
6	1669	10	1677±13	0	1
7	1624	10	1632±13	0	1
8	1649	26	1656±27	40	3
9	1679	10	1655±13	5	1
10	1732	31	1707±32	32	2
11	1800	150		60	3
12	1605	50		66	3

[a] The correction for distortion is included in the quoted range. This correction was necessary for event 10 only. The distortion correction reduced the range by 44 microns.
[b] The error introduced by the shrinkage factor uncertainty is included.

It should be noted that the ranges of the protons from Σ^+ hyperons in the π^- plates and the proton plates, are consistent with the range distribution obtained from the K-meson plates alone after correcting for the stopping power. The proton range distribution is consistent with the assumption that the protons from the Σ^+ decays are monoenergetic.

The energy of a proton of range 1669.4±8.0 microns is $E=18.84\pm0.10$ Mev. The error in the energy is the result, not only of the uncertainty in the range due to straggling, which is 0.6% in range, but also of the uncertainty in the range-energy relationship which, when the stopping power of the emulsion is accurately known, is 0.7% in range.[7] Using for the mass of the proton $(1836.13\pm0.04)m_e$,[8] and for the mass of the π^0 meson $(264.2\pm0.5)m_e$,[9] the Q for the decay of the Σ^+ hyperon by the reaction

$$\Sigma^+ \rightarrow p+\pi^0 \tag{1}$$

is found to be $Q=116.1\pm0.5$ Mev and the mass of the Σ^+ hyperon is found to be $(2327.4\pm1.0)m_e$. The errors in the Q value and the Σ^+ hyperon mass take into account the uncertainty in the π^0-meson mass.

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[8] J. W. M. Dumond and E. R. Cohen, Revs. Modern Phys. **25**, 691 (1953).
[9] The mass of the charged π mesons given by Barkas, Birnbaum, and Smith [University of California Radiation Laboratory Report UCRL-3147 (unpublished)] was used. The mass difference between the charged π meson and π^0 meson $(8.8\pm0.6)m_e$, is given by W. Chinowsky and J. Steinberger, Phys. Rev. **93**, 586 (1954).