APPARENT VIOLATION OF THE $\Delta S = \Delta Q$ RULE BY LEPTONIC Σ^+ DECAY

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Feynman and Gell-Mann suggested the selection rule $\Delta S = \Delta Q$ for strangeness-nonconserving weak interactions.[1] This hypothesis implies that leptonic decays are allowed for Σ^- hyperons, but forbidden for Σ^+ hyperons. There is some evidence that this rule is not valid for K^0 decay.[2,3] Some proposed theoretical models also do not require it.[4-6] In this Letter we report an event which is interpreted as the first example of Σ^+ decay by the mode

$$\Sigma^+ \to n + \mu^+ + \nu. \tag{1}$$

As part of a continuing program[7] of measurements of strange-particle decay in emulsion, we have thus far completely analyzed 120 examples of Σ^+ decay into near-minimum-ionizing particles, and analyzed about another 100 for electron decay. In a large part of the work, we have used a stack constructed in the form of a 9-in. cube which was exposed to K^- mesons. Practically all secondary particles originating in the center part of the stack, where the K^- mesons stop, can be brought to rest in the emulsion, and the identity and energy of each particle can be determined.

In this stack we have found an event for which the most probable interpretation is decay process (1). Figure 1 is a sketch of it. A K^- meson comes to rest at (a) and reacts with a free proton in the emulsion. This produces a Σ^+ and a π^- according

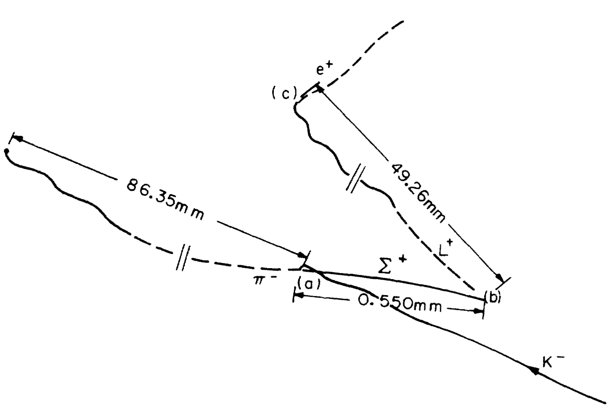

FIG. 1. Sketch showing (a) capture of a Σ^- meson ($K^- + p \to \Sigma^+ + \pi^-$); (b) decay of the Σ^+ ($\Sigma^+ \to L^+ + ?$); (c) decay of the muon ($\mu^+ \to e^+ + \nu + \bar{\nu}$). The π^- track is also shown.

to the reaction:

$$K^- + p \to \Sigma^+ + \pi^-. \tag{2}$$

The angle between the hyperon and pion was measured to be 180 deg, with an uncertainty of $\frac{1}{2}$ deg. This alone is strong evidence that the capture was by a free proton. The sign of the pion was determined by the fact that it interacted at rest, producing a "blob" at its terminus. Its range, 86.35 mm, is within the observed distribution of ranges for negative pions produced in K^- capture by a free proton. Other events of this type which we have measured yield a range of 88.66 ± 0.62 mm, with a standard deviation of 2.5 mm for a single event.

A Σ^+ hyperon that is produced in reaction (2) and comes to rest in emulsion has a range of 820.0 ± 3.5 microns with a standard deviation of 14.0 microns for a single measurement.[8] In the present case (Fig. 1), the hyperon goes a distance of 550 microns to point (b) before decaying in flight into a near-minimum secondary, L^+. At this point, the kinetic energy of the hyperon is 7.1 ± 0.1 MeV. The angle made by the decay secondary with the direction of motion of the hyperon is 144.1 ± 0.3 deg. In normal $\Sigma^+ \to \pi^+$ decay, this secondary would have an energy of 75.8 MeV and a range of 70.30 mm. Instead, we find its range to be 49.26 mm. Moreover, the secondary decays into a minimum-ionizing particle when it comes to rest at (c). By multiple scattering, we find the $p\beta$ of this secondary to be 38 ± 7 MeV/c. It is, therefore, clearly an electron, but its energy is incompatible with that expected (69.8 MeV) were the electron produced in the rare electron-decay mode of a pion. Its energy is well within the muon decay spectrum. The particle that comes to rest in the emulsion is definitely a muon. Since a Σ^+ interaction at (b) in Fig. 1 ($\Sigma^+ + n \to \pi^+ + \Lambda + n$) followed by a π-μ decay in flight can be discarded as being energetically impossible, only two interpretations of this event have been considered. These alternatives are: (A) the Σ^+ hyperon decayed into a π^+, which in turn decayed in flight into a μ^+; or (B) the hyperon decayed into a muon according to the three-body decay process (1) above.

Alternative (A) was broken down into four cases for the evaluation of each probability: (A1) A normal $\Sigma^+ \rightarrow \pi^+ + n$ decay followed by a normal decay in flight of the π^+; (A2) As in (A1), except a Coulomb deflection sufficient to destroy the kinematic fit to a π-μ decay occurs so close to the point of decay that it cannot be detected; (A3) A radiative Σ^+ decay, $\Sigma^+ \rightarrow \pi^+ + n + \gamma$, followed by a normal π-μ decay in flight; (A4) A normal or a radiative Σ^+ decay, followed by a radiative pion decay in flight.

We made a detailed examination of the L^+ track to detect evidence for a π-μ decay. All discrete deflections with greater than 4-deg space angle were carefully measured. There were seven of these as shown in Fig. 2(a). Each crossing from one pellicle to the next was checked for continuity of track direction. These deviations never exceeded 2 deg. We also measured the grain density of the entire track. The results for each 100-μ segment are shown in Fig. 2(b) as solid dots. As is seen, there are no discontinuities. The multiple scattering of the track was determined over each 2-mm segment. The results contain large errors; however, they are consistent with continuity along the track. Both the grain density and scattering follow curves expected for a muon.

To evaluate the alternative probabilities mentioned above, we carried out the kinematical calculations relating decay angles to energies and momenta by using the relativistic invariant,

$$E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2 = M_1 E_2^*. \tag{3}$$

Subscript 1 refers to the decaying particle, and subscript 2 refers to the secondary particle.

Using the calculations and the results of our measurements on the track, we consider each possible interpretation as follows:

Hypothesis (A1). In Fig. 2(a) the solid line is a curve of the angle between π and μ that would be produced in normal π-μ decay (with the constraint that the range of the muon be equal to the residual range R_{L^+}) if the Σ^+ decayed normally and the pion suffered no inelastic scatters. The observed deflections and their errors are indicated. No angle is consistent with a π-μ decay. The closest measured angle falls six standard deviations from the calculated line. The probability is less than 10^{-7} that a decay may have occurred so close to the end of the hyperon track that the change in direction would have been unobservable.

Small deflections could be missed, but as seen

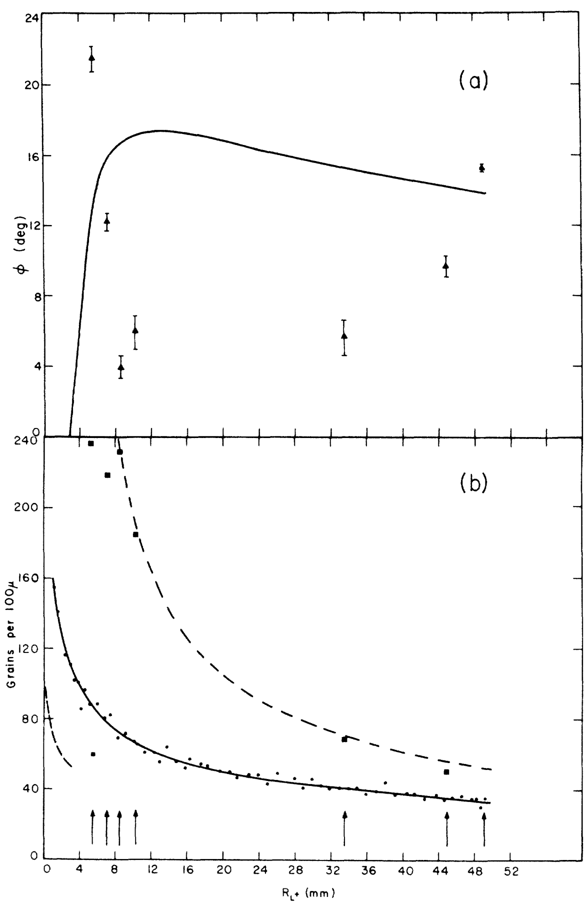

FIG. 2. (a) The solid line is the angle of deflection ϕ versus residual range of the muon, R_{L^+}, calculated for normal π-μ decay following normal Σ decay. The measured total path is a constraint. The triangles represent the measured angles; their standard deviations are shown. (b) The solid line is a fit to measured grain density of the secondary track L^+ as a function of residual range R_{L^+}. The black circles represent the measurements. The dashed line is the expected grain density of a pion decaying at any point along the track at a laboratory angle ≤ 4 deg plotted versus R_{L^+}. These dashed lines are for a π-μ decay following either normal or radiative Σ decay at $R_{L^+} \leq 4$ mm. Elsewhere only radiative Σ decay or π-μ decay following inelastic pion scattering are possible. The black squares represent the calculated pion grain density for π-μ decay following radiative Σ decay using measured angles at points of deflection and a muon energy corresponding to $R_\mu = R_{L^+}$ at those points. The arrows indicate value of R_{L^+} at which the discrete deflections occur.

from Fig. 2(a), small decay angles are important only for residual ranges less than 4 mm. Furthermore, by means of Fig. 2(b), the entire track is analyzed for the presence of π-μ decay without invoking an assumption regarding the pion energy at the decay point. Thus, for example, if the first deflection is an inelastic pion scatter, a large grain-density discontinuity would be expected if any of the subsequent deflections were interpreted as a π-μ decay point. The pion grain densities calculated on the assumption that each observed deflection is a π-μ decay are shown as black squares. Deflections greater than 4 deg are unlikely to have been missed. The pion grain density corresponding to smaller decay angles is calculated to lie on one of the dashed curves. The pion velocity was calculated by using Eq. (3) with the muon velocity given by the residual range R_{L^+}. The grain-density ratios were obtained from the results of Patrick and Barkas.[9] The lower branch of the dashed curve extends from 0 to 3 mm, because only in this interval is it energetically possible for a muon to originate from backward decay of the pion. This is because the initial pion energy cannot exceed 75.8 MeV. Normal π-μ decay is excluded at low velocities by the observed continuity of the grain densities, and at high velocities also because no observed deflection is in agreement with the kinematics of a π-μ decay. We conclude that Hypothesis (A1) does not account for our event; its probability is 10^{-6} or less.

Hypothesis (A2). The probability for a pion of mean life $\tau(2.55\times10^{-8}$ sec), momentum p, and mass M to decay in a distance s is

$$f=1-\exp\left(-M\int_0^s\frac{dx}{p\tau}\right)\approx\frac{Ms}{\tau}\langle p^{-1}\rangle. \tag{4}$$

Because a sample of 120 Σ decays was examined, the probability, P, that one of the pions might decay is 120 F. The distance to the first deflection is designated s_1, and the probability for any one of the pions to decay in that interval is P_1. If the first deflection is not a decay, the probability that one of the pions would decay in the distance s_2 to the second deflection is P_2. Similar probabilities P_3, P_4, etc., correspond to the successive deflections.

Since the measured angles are not those calculated for π-μ decay, one can assume that at each deflection on the L^+ track the observed angle differs from the decay angle because a Coulomb deflection occurred close to the point of decay. We calculate the number, n, of Coulomb deflections per micron of path that produce a net space-angular change equal to or exceeding the observed difference, Δ, in degrees. It is $n=1.54/(p\beta\Delta)^2$. About 10 microns of path are required to detect such an angular change. Thus at the ith deflection a probability,

$$Q_i=(15.4/\Delta_i^{\,2})[1/(p\beta)_1^{\,2}+1/(p\beta)_2^{\,2}],$$

exists that a Coulomb deflection might have altered the apparent decay angle. Here $(p\beta)_1$ and $(p\beta)_2$ are the respective scattering rigidities before and after the postulated π-μ decay.

Only the first three deflections need be considered, because the rest are eliminated by the observed continuity of grain density. They are analyzed in Table I. The sum $\sum_i P_iQ_i=2.1\times10^{-5}$ is the probability that one of the three deflections is a normal π-μ decay.

We have also examined the emulsion for distortion. The only critical angle is the first one, where the difference between the measured and predicted angle is 1.51 ± 0.20 deg. Fortunately, a fast particle traversed the emulsion adjacent to and nearly parallel to the track under study. No change in direction caused by distortion could be detected in it. Hypothesis (A2) then has a probability of no more than a few parts in 10^5.

Hypothesis (A3). By the same argument as used for eliminating inelastic pion scattering followed by decay under Hypothesis (A1), radi-

Table I. Probabilities, calculated for each observed deflection, that an event is a normal π-μ decay masked by an adjacent Coulomb scatter.

Δ (deg)	s (cm)	$(p\beta)_1$	$(p\beta)_2$	f	Q	PQ
1.5 ± 0.2	0.025	126	91	2.75×10^{-5}	1.24×10^{-3}	4.1×10^{-6}
4.5 ± 0.6	0.434	121	87	4.87×10^{-4}	1.5×10^{-4}	8.7×10^{-6}
9.6 ± 0.7	1.582	109	74	1.86×10^{-3}	3.7×10^{-5}	8.3×10^{-6}
						Sum = 2.1×10^{-5}

ative Σ decay is found to be an improbable explanation of the event. For some deflections, one-pion energy is possible, for others two, but all except the one at $R_{L^+} = 49$ mm are eliminated by the continuity of grain density. The remaining deflection is hardly possible for π-μ decay at any pion energy. It exceeds by six standard deviations the largest angle possible subject to the muon range constraint. The corresponding probability that this process might account for the event is 2×10^{-7}.

Hypothesis (A4). Since the behavior of track L^+ cannot be explained by invoking radiative or normal Σ decay followed by a normal π-μ decay, the consequences of radiative pion decay have been examined.

Since the muon-plus-pion path length is fixed, the expected discontinuity in grain density can be calculated at every point of the track if a radiative pion decay follows a normal Σ decay. This discontinuity is less than 15% only in the first portion of the path, where the residual range exceeds 22 mm. In this portion of the path, radiative pion decay could not be detected if the direction of emission of the muon were nearly backward. (The constraint on the particle range mentioned above makes forward decay impossible.) About one in two hundred pions would be expected to decay in this path segment. The probability[10] of radiative decay is 1.23×10^{-4}. Then out of a sample of 120 pions from normal Σ^+ decay, the number that would be expected to decay radiatively in such a way that the point of decay could not be detected by a discontinuity in grain density is certainly less than 10^{-5}.

The *a priori* probability of alternative (B) is the question. Our estimate of this probability would be affected, were we to find that a feature of the track was not characteristic of a muon. The grain density and scattering, however, follow curves expected for a muon. The deflection angles are compatible with Coulomb scattering of a light particle in the high-density medium of emulsion. The first deflection point (15.3 deg) has the smallest probability of being such a scatter because it occurs at a $p\beta$ of 91 MeV/c. However, a muon scattering angle exceeding the calculated π-μ decay angle (13.8 deg) is expected once in an emulsion path of 57 cm. At this angle, the nuclear electromagnetic form factor does not yet seriously affect the scattering probability.

In conclusion, of the plausible interpretations of this event, muonic decay of the hyperon [alternative (B)] is the only one that is probable. In the rest frame of the Σ, the muon momentum is 136 MeV/c – very close to 132 MeV, the peak calculated for three-body phase-space distribution. Therefore, we are reporting this event although we are well aware that, with notable exceptions, it is difficult to evaluate the weight of a single observation. Clearly, present searches for leptonic Σ^+ decay should be continued.

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