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THEORY OF Σ-HYPERON DECAYS

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(Received May 12, 1960)

In this note we consider a model of the Σ hyperon as a bound state of a Λ^0 and a pion. By means of this model, we find it possible to explain some observed features of Σ decay simply in terms of the observed properties of Λ^0 decay.

For simplicity we shall consider the bound state to be an S state. This would lead to the following obvious features: (a) The spin of the Σ would be 1/2. (b) The isotopic spin of the Σ would be 1. (c) The relative parity of the Σ and Λ would be odd.[1]

Properties (a) and (b) are known to be satisfied.[2] Property (c) has not yet been investigated. However, a model of the Σ as a bound Λ and pion in a $P_{1/2}$ state will give similar predictions to those that follow.

We consider the following three decay modes of the Σ hyperons:

$$\Sigma^+ \to \pi^+ + n, \qquad (1)$$

$$\Sigma^+ \to \pi^0 + p, \qquad (2)$$

$$\Sigma^- \to \pi^- + n. \qquad (3)$$

The mechanism for the decay is assumed to be the decay of the Λ hyperon within the Σ into a pion and a nucleon, with subsequent absorption by the nucleon, of either the pion within the Σ or the pion from the Λ decay, to form the appropriate final state of reactions (1), (2), or (3). The virtual decay of the Λ particle will be assumed to satisfy the $\Delta I = \frac{1}{2}$ rule and time-reversal invariance. This decay will be assumed to proceed with an amplitude A into an S-wave pion-nucleon system and with either an amplitude A or an amplitude $-A$ into a P-wave pion-nucleon system. For the present discussion, whose purpose is a qualitative picture of Σ decays, we will neglect multiple-scattering effects in the pion-nucleon systems of isotopic spin and total angular momentum $\frac{1}{2}$, and will consider the amplitude A as real. The approximate equality in magnitude of the S- and P-wave amplitudes is inferred from the assumption of a near maximal asymmetry parameter in the decay of a real Λ.[3] The positive and negative values of the P-wave amplitude correspond to the asymmetry parameter, α_Λ, equal to +1 and -1, respectively. The nucleon from the decay of the Λ will absorb a pion in a P wave relative to it. This may be the pion from P-wave decay of the Λ, in which case the absorption will be characterized, again approximately, by the real amplitude B. A second possibility is that the nucleon may absorb, via a P-wave interaction, the pion within the Σ, which is in an S state relative to the center of mass of the pion-nucleon system resulting from the Λ decay. This absorption will be characterized approximately by a real amplitude, B'.

With these definitions and making standard use of the Clebsch-Gordan coefficients, we construct the amplitudes for the reactions (1), (2), and (3).

$$\Sigma^+ = (\pi^+\Lambda)_S \to A\pi_S^+\{-(\tfrac{2}{3})^{1/2}(\pi^-p)+(\tfrac{1}{3})^{1/2}(\pi^0n)\}_S \pm A\pi_S^+\{-(\tfrac{2}{3})^{1/2}(\pi^-p)+(\tfrac{1}{3})^{1/2}(\pi^0n)\}_P \to \pm AB(\pi^+n)_S, \quad (4)$$

$$\Sigma^+ = (\pi^+\Lambda)_S \to A\pi_S^+\{-(\tfrac{2}{3})^{1/2}(\pi^-p)+(\tfrac{1}{3})^{1/2}(\pi^0n)\}_S \pm A\pi_S^+\{-(\tfrac{2}{3})^{1/2}(\pi^-p)+(\tfrac{1}{3})^{1/2}(\pi^0n)\}_P \to \tfrac{1}{3}\sqrt{2}\,AB'(\pi^0p)_P \pm \tfrac{1}{3}\sqrt{2}\,AB'(\pi^0p)_S, \quad (5)$$

$$\Sigma^- = (\pi^-\Lambda)_S \to A\pi_S^-\{-(\tfrac{2}{3})^{1/2}(\pi^-p)+(\tfrac{1}{3})^{1/2}(\pi^0n)\}_S \pm A\pi_S^-\{-(\tfrac{2}{3})^{1/2}(\pi^-p)+(\tfrac{1}{3})^{1/2}(\pi^0n)\}_P \to \pm AB(\pi^-n)_S \pm \tfrac{2}{3}AB'(\pi^-n)_P \pm \tfrac{2}{3}AB'(\pi^-n)_S. \quad (6)$$

In these equations the subscripts S or P on $(\pi\Lambda)$ and (πN) denote the orbital angular momentum of the pion and the baryon within the parenthesis; the subscripts S or P on the bracketed quantities, $\{\ldots\}$, denote the orbital angular momentum of the pion-nucleon systems within the brackets; the subscript S on the symbol π standing outside of the brackets denotes the orbital angular momentum of this pion relative to the center of mass of the pion-nucleon systems within the brackets. Products like AB are symbolic in that they will involve integrations over the momenta and a summation over the spin of a specific intermediate-state configuration.

The following predictions follow from our model, the aforementioned approximations, and Eqs. (4) - (6): (a) The decay $\Sigma^+\to\pi^+ + n$ results in a pure S-wave final state and the asymmetry parameter for this mode is zero. (b) The asymmetry parameter in the decay $\Sigma^+\to\pi^0+p$ is nonzero and it has the same sign as the asymmetry parameter in Λ decay. Under the assumption that the asymmetry parameter in Λ decay is maximal, the decay $\Sigma^+\to p+\pi^0$ proceeds with an equal admixture of S- and P-wave final states and consequently a maximal asymmetry parameter. (c) The decay $\Sigma^-\to\pi^- + n$, in general, involves a mixture of S- and P-wave final states. If we choose the single parameter in the theory, $AB'/AB = -3/2$, the decay $\Sigma^-\to\pi^- + n$ results in a pure P-wave final state and the asymmetry parameter for the mode is zero. It then follows that the three decay rates for the reactions (1), (2), and (3) are equal. If these three rates are not equal, the asymmetry parameter in the decay $\Sigma^-\to\pi^- + n$ will be nonzero.

We consider the leptonic decay modes (with nucleon emission) of the hyperons. It is immediately evident that the model contains the beta (and muon) decay of the Σ^- via the beta (and muon) decay of the Λ hyperon within the Σ^-:

$$\Sigma^- = (\pi^-\Lambda)_S \to a\pi_S^-(e^-\bar{\nu}p) \to \sim -(2/3)^{1/2}aB'(e^-\bar{\nu}n), \quad (7)$$

where a is the amplitude for the virtual beta decay of the Λ. Similarly the beta (and muon) decay of the Σ^+ would in general be allowed if there existed a decay of the Λ^0 of the form $\Lambda^0\to\pi^- + e^+ + n + \nu$. However, if one makes the simple additional assumption that all weak interactions proceed only through four-fermion couplings, then this mode of the Λ^0 is not allowed and the Σ^+ cannot undergo beta (or muon) decay. Also decays such as $\bar{K}^0\to e^+ + \pi^- + \nu$ which have $\Delta S/\Delta Q = -1$ are forbidden. It is necessary to forbid such modes in the conventional theory, to avoid violating the $\Delta S \neq 2$ rule for the weak interactions.

We note that, as a crude exercise, we can calibrate the amplitude A from real Λ decay and amplitude B' from real Σ^- decay. Then the ratio of the rate for Λ beta decay to that for Σ^- beta decay may be obtained. Carrying out this exercise gives a value for this ratio of ~0.1, which is not very different from the ratio of ~0.17 obtained from phase space considerations alone.[4]

In conclusion, we state that the theory gives a simple basis for predicting a number of features of Σ decays that present experiments seem to indicate[5,6]: (a) Decay modes (1) and (3) seem to exhibit small asymmetry parameters and decay mode (2) a large asymmetry parameter. (b) As a consequence of (a) and the $\Delta I = \frac{1}{2}$ rule, the decay rates for the reactions (1), (2), and (3) are approximately equal. (c) The Σ^- will undergo leptonic decay and the Σ^+ will not undergo leptonic decay (with nucleon emission) if one assumes that the weak interactions go only by way of four-fermion couplings. The theory predicts that the sign of the asymmetry parameter for the decay mode (2) is the same as that of the asymmetry parameter in Λ decay, and that the two asymmetry parameters are comparable in magnitude. For odd relative Σ - Λ parity, the present approximate treatment indicates that the decay mode (1) involves a pure S state and the decay mode (3) a pure P state; a measurement of the recoil neutron polarizations could check these consequences of the theory. The asymmetry parameter for the decay mode (3) may be nonzero if the three decay rates are not precisely equal.

If the Σ is a bound $P_{1/2}$ state of Λ^0 and a pion, then the only difference would be that the $\Sigma^+ \rightarrow \pi^+ + n$ decay would be all in P state rather than S state.

One of the authors (S. B.) wishes to thank Professors Sam Schweber and Kenneth Ford for their comments. The other would like to extend similar thanks to Professor G. Feinberg and Professor T. D. Lee.

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ELECTROMAGNETIC CORRECTIONS TO THE DECAYS OF THE MUON, O^{14}, AND THE NEUTRON*

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According to the conserved vector current hypothesis of Feynman and Gell-Mann[1] for the weak interactions, the vector coupling constant G_V should be the same for μ decay and nuclear β decay. However, the values of G_V determined from the experimental muon lifetime and the decay rate in the $0^+ \rightarrow 0^+$ transition $O^{14}(\beta^+)N^{14*}$ differ by a few percent after inclusion of the radiative corrections discussed by a number of authors.[2] Kinoshita and Sirlin predict a muon lifetime of $\tau_\mu = (2.31 \pm 0.05) \times 10^{-6}$ sec on the basis of an O^{14} half-life of 72.5 ± 0.5 sec,[3] and a β^+ end-point kinetic energy of 1810 ± 8 kev.[4] With a recent revised end-point energy of 1800 ± 6.5 kev,[5] the predicted lifetime becomes $\tau_\mu = (2.26 \pm 0.05) \times 10^{-6}$ sec.[6] These numbers are to be compared with the observed lifetime $\tau_\mu = (2.21 \pm 0.005) \times 10^{-6}$ sec.[7] While the discrepancy may not be serious, it should be noted that the calculated radiative corrections are subject to certain ambiguities: the perturbation theory approach used in the calculations of reference 2 yields finite results in the muon case,[8] but the calculated corrections for nuclear β decay are ultraviolet divergent. The cutoff-dependent term in the correction to the decay rate, $\Delta\Gamma/\Gamma_0 = (3\alpha/2\pi) \ln(\Lambda^2/m_p m_e)$, was evaluated by choosing a cutoff Λ equal to the proton mass m_p, in the expectation that the proper inclusion of nuclear electromagnetic form factors would introduce a natural cutoff of the virtual photon contributions near this value. The resulting expression $\Delta\Gamma/\Gamma_0 = (3\alpha/2\pi) \ln(m_p/m_e) = 0.026$ represents the dominant part of the quoted radiative correction. This rather unsatisfactory situation makes it desirable to re-examine the problem from a somewhat different point of view. In the present paper, we wish to discuss the results of a calculation based on the techniques of