from which, according to (6),

$$\alpha\bar{P}=0.44\pm0.11.^{5} \quad (8)$$

If parity were conserved, and hence $\alpha=0$ were the true value, we would have $N_{\rm up}=N_{\rm down}$, on the average. The odds against a statistical fluctuation as large or larger than that which would be needed to give our result (7) are better than 10^4 to 1. We conclude that parity conservation is violated in Λ decay.

We can compare our value of $|\alpha|$ with the maximum value of $|\alpha|$ allowed by invariance under *charge conjugation*. Using the *TCP* theorem, Gatto[6] has calculated this maximum value and finds $|\alpha|\leqslant0.18\pm0.02$, which is inconsistent with our result (8) (since $|\bar{P}|\leqslant1$). We conclude that the Λ decay interaction violates charge-conjugation invariance as well as parity conservation.

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[1] In nuclear emulsion many K^- mesons have been brought to rest and captured from atomic orbits according to the reaction $K^-+p\rightarrow\Sigma^\pm+\pi^\pm$, where p represents a proton which is part of a nucleus. The Σ and π tracks are in general not collinear, so one can define a "production plane," and look for an up-down asymmetry in Σ decay. Compiling the emulsion data and using the notation of this letter, one finds for the mode $\Sigma^+\rightarrow p+\pi^0$, $\alpha_0\bar{P}=-0.37\pm0.19$, for $\Sigma^+\rightarrow n+\pi^+$, $\alpha_+\bar{P}=-0.36\pm0.21$, but for $\Sigma^-\rightarrow n+\pi^-$, $\alpha_-\bar{P}=-0.13\pm0.26$. We wish to thank the Berkeley, Göttingen, Livermore, and Naval Research Laboratory emulsion groups for their private communications.

[2] Lee, Steinberger, Feinberg, Kabir, and Yang, Phys. Rev. **106**, 1367 (1957).

[3] Analysis of the double V^0's shows that reaction (1) is about three times as common as reaction (3). R. Gatto has shown (private communication) that the magnitude of the polarization of such secondary Λ's (averaged over the Σ^0 decay solid angle) is $\frac{1}{3}$ that of the Σ^0's .Thus even if the Σ^0's were highly polarized their contribution would have a very small effect on our result.

[4] We estimate that in our sample the contamination of $K^0\rightarrow2\pi$ decays allowed by this criterion is about 15%. We are indebted to Dr. Melvin Schwartz for pointing out this simple way of eliminating most of the K^0's from the single V^0's.

[5] This result is in excellent agreement with results of similar experiments performed at Brookhaven and analyzed by the Bologna, Columbia, Michigan, and Pisa groups. Those data were compiled at the recent Venice-Padova Conference, 1957; they are $N_{\rm up}$—129, $N_{\rm down}=81$, so $\alpha\bar{P}=0.46\pm0.14$. Their asymmetry for $\Sigma^-\rightarrow n+\pi^-$ is much smaller, also in agreement with our result and that for emulsion.

[6] R. Gatto, Phys. Rev. **108**, 1103 (1957), following letter, and private communications.

Test of Charge-Conjugation Invariance in Hyperon Decay*

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The evidence for noninvariance under charge conjugation (C) in β decay and in the π and μ decays was based on a theorem due to Lee, Oehme, and Yang, which states that, in decays where final-state interactions can be neglected, no pseudoscalars of the form $(\boldsymbol{\sigma}\cdot\mathbf{p})$ can appear in the decay distribution if C is conserved.[1] In the decay of a hyperon into nucleon plus pion, a strong final-state interaction is present and therefore a quantitative estimate of the limits imposed by C invariance to the coefficients of the $(\boldsymbol{\sigma}\cdot\mathbf{p})$ terms is necessary before drawing conclusions on the question of conservation of C for such decays. Recent experimental results on up-down asymmetry in $\Lambda\rightarrow p+\pi^-$ indicate an asymmetry parameter $|\alpha|>0.44\pm0.11$.[2] From the limitation $|\alpha|<0.18\pm0.02$, that we give here for $\Lambda\rightarrow p+\pi^-$ under the assumption of C invariance we can conclude that C is not conserved in Λ decay. It might be appropriate to remark that the argument is based on the *TCP* theorem—all evidence so far against conservation of C is based on the validity of the *TCP* theorem.

We write the final amplitude from Λ decay in the form $T\chi_i\zeta_i$, where χ_i and ζ_i are the initial spin and isotopic spin states respectively, and T is a matrix in the spin and isotopic spin spaces. In the expansion $T=T_{\frac{1}{2}}+T_{\frac{3}{2}}+T_{\frac{5}{2}}+\cdots$, where T_J produces a change $\Delta I=J$ in isotopic spin, only $T_{\frac{1}{2}}$ and $T_{\frac{3}{2}}$ contribute to $\Lambda\rightarrow$nucleon$+\pi$. They are of the form $T_{\frac{1}{2}}=g_1+h_1(\boldsymbol{\sigma}\cdot\mathbf{k})$, $T_{\frac{3}{2}}=g_3+h_3(\boldsymbol{\sigma}\cdot\mathbf{k})$, where the g's and h's are complex numbers, $\boldsymbol{\sigma}$ is the Pauli spin operator, and $\mathbf{k}$ is a unit vector in the direction of the emitted pion. The decay distribution for $\Lambda\rightarrow p+\pi^-$ is given by

$$G(\mathbf{k})=1+\langle\boldsymbol{\sigma}\rangle_\Lambda\cdot\mathrm{Tr}\,[T_1^\dagger\boldsymbol{\sigma}T_1]/\mathrm{Tr}\,[T_1^\dagger T_1]$$
$$=1+\alpha(\Lambda\rightarrow p-)\langle\boldsymbol{\sigma}\rangle_\Lambda\cdot\mathbf{k}$$

where $\langle\boldsymbol{\sigma}\rangle_\Lambda$ is the Λ polarization vector, T_1 is that part of T which contributes to decay into $p+\pi^-$, and $\alpha(\Lambda\rightarrow p-)$ is the asymmetry parameter.[3] If C is conserved we can write, using the *TCP* theorem,

$$g_1=G_1e^{i\alpha_1},\quad g_3=G_3e^{i\alpha_3},\quad h_1=iH_1e^{i\alpha_{11}},\quad h_3=iH_3e^{i\alpha_{31}},$$

where the G's and H's are real numbers, and the α's are the relevant nucleon-pion phase shifts for a total kinetic energy in the center-of-mass system equal to the Q value in the decay.[1] With such substitutions we can write the asymmetry parameter in the form

$$\alpha(\Lambda\rightarrow p-)=f(\Delta)(Av_1v_2+Bv_1v_4+Cv_2v_3+Dv_3v_4)$$

where $f(\Delta)=(1+\frac{1}{3}\Delta)/(1+\frac{1}{2}\Delta)$, Δ being defined by:

(relative frequency of $\Lambda\to p+\pi^-$ to $\Lambda\to n+\pi^0$) $=2+\Delta$; A, B, C, and D are parameters proportional to the sines of differences of phase shifts and the real numbers v_i have to satisfy $\sum v_i^2=1$. Defining a vector v with components v_i, this condition can be written as $(v,v)=1$, and $\alpha(\Lambda\to p-)$ can be put in the form $f(\Delta)(v,mv)$ where m is the symmetric 4×4-matrix associated to the quadratic form in $\alpha(\Lambda\to p-)$. The maximum and the minimum of $\alpha(\Lambda\to p-)$ are therefore given by the maximum and minimum eigenvalues, respectively, of the matrix $f(\Delta)m$. Such two eigenvalues have the same magnitude, and by direct calculation one finds

$$|\alpha(\Lambda\to p-)|\leq(1/2\sqrt{2})f(\Delta)[S+(S^2-P^2)^{\frac{1}{2}}]^{\frac{1}{2}},$$

where

$$S=4\sin^2(\alpha_1-\alpha_{11})+2\sin^2(\alpha_3-\alpha_{11})+2\sin^2(\alpha_1-\alpha_{31})+\sin^2(\alpha_3-\alpha_{31}),$$

and $P^2=16\sin^2(\alpha_1-\alpha_3)\sin^2(\alpha_{11}-\alpha_{31})$. Taking the value 0.32 ± 0.05 reported by Steinberger's group for the fraction of Λ particles undergoing neutral decay,[4] and for the pion-nucleon phase shifts the values reported by Anderson,[5] we find $|\alpha(\Lambda\to p-)|\leq0.18\pm0.02$, if charge-conjugation invariance is satisfied. Similar limitations, under the hypothesis of conservation of C, can be given for the asymmetry parameters of Σ decays. We assume spin $\frac{1}{2}$ for Σ. The limitation $|\alpha(\Sigma^-\to n-)|\leq|\sin(\alpha_3-\alpha_{31})|$ for Σ^- decay, where only one final isotopic spin state can occur, is given in reference 3. The phase shifts are taken at an energy equal to the decay Q value. We find that $|\alpha(\Sigma^+\to p0)|\leq(1/2\sqrt{2})\times g(\Gamma)[R+(R^2-Q^2)^{\frac{1}{2}}]^{\frac{1}{2}}$, where $g(\Gamma)=\frac{4}{3}(1+\frac{1}{2}\Gamma)$, Γ being defined by (relative frequency of $\Sigma^+\to n+\pi^+$ to $\Sigma^+\to p+\pi^0$) $=1+\Gamma$,

$$R=\sin^2(\alpha_1-\alpha_{11})+2\sin^2(\alpha_3-\alpha_{11})+2\sin^2(\alpha_1-\alpha_{31})+4\sin^2(\alpha_3-\alpha_{31}),$$

$$Q^2=16\sin^2(\alpha_1-\alpha_3)\sin^2(\alpha_{11}-\alpha_{31});$$

$$|\alpha(\Sigma^+\to n+)|\leq(1/2\sqrt{2})h(\Gamma)[U+(U^2-Q^2)^{\frac{1}{2}}]^{\frac{1}{2}},$$

where

$$h(\Gamma)=\tfrac{4}{3}(1+\tfrac{1}{2}\Gamma)/(1+\Gamma),$$

and

$$U=4\sin^2(\alpha_1-\alpha_{11})+2\sin^2(\alpha_3-\alpha_{11})+2\sin^2(\alpha_1-\alpha_{31})+\sin^2(\alpha_3-\alpha_{31}).$$

Taking the value 0.45 ± 0.06 for the ratio ($\Sigma^+\to n+\pi^+$) to the total Σ^+ decay rate,[6] and using the nucleon-pion phase shifts from reference 5, we find $|\alpha(\Sigma^-\to n-)|\leq0.14\pm0.06$, $|\alpha(\Sigma^+\to p0)|\leq0.27\pm0.04$, $|\alpha(\Sigma^+\to n+)|\leq0.37\pm0.06$, if C is conserved. For hyperons with spin $\frac{3}{2}$ the decay distributions will not in general be describable with a single parameter α. If C is conserved, the total asymmetry will still be severely limited for Λ decay, but presumably only weakly limited for Σ decay, because of the large α_{33}. One argument for Λ spin $\frac{1}{2}$, that based on the mesonic-decay to nonmesonic-decay ratio in hyperfragments,[7] may turn out to be inaccurate if a large p wave is observed in Λ decay. Because of the low final momentum, a large up-down asymmetry in Λ decay will be an important test for theories which predict the relative amount of parity-conserving and parity-nonconserving interactions on the basis of a universal interaction. The knowledge of the frequency ratio $(\Lambda\to p-)/(\Lambda\to n0)$, of $\alpha(\Lambda\to p-)$, and of $\alpha(\Lambda\to n0)$, together with the total decay rate, would constitute essential information on the Λ-decay matrix.[8] If the present value for the Λ branching ratio is taken as an evidence—in any case incomplete—in favor of $\Delta I=\frac{1}{2}$ [9] in Λ decay, then $\alpha(\Lambda\to n0)$ is predicted to be equal to $\alpha(\Lambda\to p-)$.

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† On leave of absence from Istituto di Fisica dell' Universita' di Roma, Italy.

[1] Lee, Oehme, and Yang, Phys. Rev. **106**, 340 (1957).

[2] Crawford, Cresti, Good, Gottstein, Lyman, Solmitz, Stevenson, and Ticho [Phys. Rev. **108**, 1102 (1957) (preceding letter)]. The Λ spin is assumed to be $\frac{1}{2}$.

[3] α is the same as in Lee, Steinberger, Feinberg, Kabir, and Yang, Phys. Rev. **106**, 1367 (1957).

[4] Eisler, Plano, Samios, Schwartz, and Steinberger, Nuovo cimento, **6**, 1700 (1957).

[5] H. L. Anderson, in *Proceedings of the Sixth Annual Rochester Conference on High-Energy Physics* (Interscience Publishers, Inc., New York, 1956), 1–20. Errors in the phase shifts are estimated from the error matrix given in this reference.

[6] Alvarez, Bradner, Falk-Vairant, Gow, Rosenfeld, Solmitz, and Tripp, University of California Radiation Laboratory Report UCRL-3775 (unpublished).

[7] M. Ruderman and R. Karplus, Phys. Rev. **102**, 247 (1956).

[8] Such data are still insufficient to determine uniquely the decay matrix in its nonrelativistic approximation, even under the assumption of time-reversal invariance. In fact, both the total decay rates and the asymmetries remain unchanged if the values of the s and p final amplitudes are interchanged. Such ambiguity can be resolved, for both Λ and Σ decay, either by measurement of the polarization of the emitted nucleon from the polarized hyperon, or by exploring the decay matrix off the energy shell. This last possibility is, most conveniently, offered (at least for Λ) by the occurrence of the nonmesonic decay mode in hyperfragments (radiative decays, as due to internal bremsstrahlung, are expected to depend essentially on values of the decay matrix very near the energy shell).

[9] M. Gell-Mann and A. Pais, *Proceedings of the 1954 Glasgow Conference on Nuclear and Meson Physics* (Pergamon Press, London, 1955), p. 342; R. Gatto, Nuovo cimento **3**, 318 (1956); G. Wentzel, Phys. Rev. **101**, 1215 (1956).

Parity Nonconservation and the β Spectrum of RaE

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SINCE Wu *et al.*[1] showed that space inversion invariance is violated, the study of β decay entered into a new stage. At present we have not yet reached any