of trapezoidal shape and of the width predicted from the geometry of the apparatus. When the detector was centered in the image of the beam, the counting rate produced by the beam was 34 per second.

The data of the experiment are shown in Table I. The quantity of interest is the decrease in the counting rate, arising from the beam, when the magnetic field is applied. However, the magnetic field affects the electron trajectories in the phototube and an appropriate correction must be made. We take for the relative sensitivity of the phototube the ratio of the background count (beam off) with the field off and on. We therefore have for the ratio of the intensity with field off and on the quantity

$$R = \left(\frac{A - B}{C - D}\right)\frac{D}{B} = \left(\frac{A}{B} - 1\right)\left(\frac{C}{D} - 1\right)^{-1} = 1 - \delta. \qquad (1)$$

From the data in Table 1, we find $\delta = 0.007 \pm 0.013$. The image of the beam in the detector

Table I. Total number of counts observed for various experimental conditions.

	Condition		
Observation	Magnet	Beam	Total counts
A	On	On	202 368
B	On	Off	118 524
C	Off	On	204 864
D	Off	Off	119 616

plane is a trapezoid. A detailed calculation of the decrease in the number of particles incident on the detector slit, symmetrically placed within the beam image, can give an upper limit to the magnetic moment of the He^6 nucleus if a spin is assumed. In Fig. 1 is shown the quantity δ as a function of μ for $I = 1$. The upper limit of the magnetic moment is thus 0.16 nm and the most probable experimental value is 0.09 nm; however, the probability of a zero moment is considerably greater than that of a moment as great as 0.16 nm. The quantity δ is quite sensitive to the aperture of the apparatus and a reduction in aperture would allow a determination of μ within closer limits. However, the large background in the present experiment, which would not be reduced by a decrease in aperture, makes this reduction of limited value.

It is difficult to construct a model of the He^6 nucleus which would ascribe a spin to it and a moment as small as 0.16 nm. It therefore seems highly probable on experimental grounds that the spin of the He^6 nucleus is indeed zero.

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[1] R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958).

[2] B. M. Rustad and S. L. Ruby, Phys. Rev. 97, 991 (1955).

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[4] Hermannsfeldt, Burman, Stähelin, Allen, and Braid, Phys. Rev. Lett. 1, 61 (1958). The work of these authors indicates that the He^6 beta-decay interaction is axial vector, in agreement with Feynman and Gell-Mann, and in disagreement with Rustad and Ruby.

[5] We are indebted to J. Vise and B. Rustad for the careful determination of the half-life of the current sample of He^6.

SEARCH FOR PARITY NONCONSERVATION IN THE ASSOCIATED PRODUCTION PROCESS*†

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Parity nonconservation was first established experimentally in the weak interactions of β decay, π decay, and μ decay. Subsequently, the observation of a large up-down decay asymmetry of Λ's with regard to the production plane, in the reaction sequence

$$\pi^- + p \to \Lambda + K^0, \qquad (1)$$

$$\Lambda \to p + \pi^-, \qquad (2)$$

demonstrated that parity is also not conserved in hyperon decay.[1,2]

Experiments involving nuclear energy levels demonstrate that parity is conserved to a high degree in strong interactions between nuclei.[3] However, it has been pointed out by Soloviev[4] and by Drell, Frautschi, and Lockett[5] that this evidence may have little bearing on the question of whether parity is conserved in strong interactions involving strange particles.[6]

The observed large asymmetry in the Λ decay (2) furnishes a powerful means of investigating this question, through determination of the direction and magnitude of the Λ polarization. If parity is conserved in the associated production process (1), there can be no component of Λ polarization and hence no decay asymmetry in the production plane.[7] Further, Drell et al. point out (and we repeat their observation in the latter part of this paper) that if some parity-nonconserving amplitude is present in the production (1), it cannot fail to yield a polarization component in the production plane.[5] (This conclusion depends on the presence of the already established asymmetry normal to the production plane.[1,2]) Consequently, one can experimentally determine an upper limit to the parity-nonconserving contribution to (1).

We have analyzed in detail 236 events of the type (1) + (2), produced by 1.12-Bev/c pions incident upon a liquid hydrogen bubble chamber. Our results are perfectly consistent (χ^2 probability of 30%) with zero decay asymmetry in the production plane. The data are thus a good fit to the hypothesis that parity is conserved in associated production. If, in order to establish an upper limit, we adopt the hypothesis that parity is not conserved in the production, we find that the fractional intensity of the parity-nonconserving contribution is 0.07 ± 0.08. The details of the analysis follow.

The hyperon polarization vector $\vec{P}(\theta)$ in the hyperon rest frame is given by specifying its three components $P_k(\theta)$ with regard to a right-handed orthogonal coordinate system consisting of two axes, No. 1 and No. 2, lying in the production plane, and an axis No. 3 perpendicular to the production plane, in the direction of $\vec{P}_i \times \vec{P}_\Lambda$.

The choice of direction for axis No. 1 is somewhat arbitrary. If all the production occurred at a single angle θ (θ is the c.m. production angle of the hyperon with respect to the incident pion), this choice would be immaterial in determining the magnitude $(P_1^2 + P_2^2)^{\frac{1}{2}}$ of the polarization component in the production plane. Similarly, a plot of $[P_1^2(\theta) + P_2^2(\theta)]^{\frac{1}{2}}$ vs θ is, of course, invariant against this choice. We will first consider this magnitude, before considering particular orientations of axis No. 1.

We divide the production angle θ into six equal histogram intervals in $\cos\theta$. The three average polarization components in each interval are given by

$$a_k(\theta) \equiv \alpha P_k(\theta) = [3/N(\theta)] \sum_{j=1}^{N(\theta)} n_k^{\,j}(\theta) \pm [(3-a_k^2)/N(\theta)]^{\frac{1}{2}},$$

where k is 1, 2, 3, and where $n_k(\theta)$ is the direction cosine of the jth hyperon's decay pion along axis No. k, in the hyperon rest frame. (The magnitude of α, as determined from these same events, lies between 0.73 ± 0.14[8] and 1.0.)

We wish to test the hypothesis that parity is conserved in Reaction (1). Then the expectation values for the decay asymmetry components in the production plane are $\langle a_1 \rangle = \langle a_2 \rangle = 0 \pm \sigma^{\frac{1}{2}}$, where $\sigma \equiv 3/N(\theta)$ is the mean square deviation in a_k due to statistical fluctuations. If a_1 and a_2 are normally distributed about zero, then for the magnitude $a(\theta) = +[a_1^2(\theta) + a_2^2(\theta)]^{\frac{1}{2}}$ the probability distribution is

$$P(a)\,da = \exp(-a^2/2\sigma)\,(a\,da/\sigma),$$

so that, from statistical fluctuations alone, we have

$$\langle a \rangle = [(\pi/2)\sigma]^{\frac{1}{2}}, \quad \langle a^2 \rangle = 2\sigma, \quad \text{and} \quad [\langle (a - \langle a \rangle)^2 \rangle]^{\frac{1}{2}} = [(2-\pi/2)\sigma]^{\frac{1}{2}}.$$

In Fig. 1, we plot

$$a(\theta) - [(\pi/2)\sigma]^{\frac{1}{2}} \pm [(2-\pi/2)\sigma]^{\frac{1}{2}} \text{ vs } \theta.$$

It is evident from Fig. 1 that there is no indication of a statistically significant real effect. To express this numerically, we perform a χ^2 test on the hypothesis that $a_1(\theta) = a_2(\theta) = 0$, and apply it to the six histogram intervals plotted. We obtain $\chi^2 = 14.1$, with $2\times 6 = 12$ degrees of freedom.[9] The probability for $\chi^2 \geq 14.1$ is 0.30. That is, the data give an excellent fit to the hypothesis that parity is conserved in associated production. Since $a(\theta)$ is invariant, a real effect cannot have escaped detection by an unlucky choice of coordinate systems.

We now make particular choices for axis No. 1 and average the polarization vector over θ, the production angle for the hyperon. At least three interesting directions suggest themselves. They are illustrated in Fig. 2.[10] With a real parity-nonconservation effect, one of these sys-

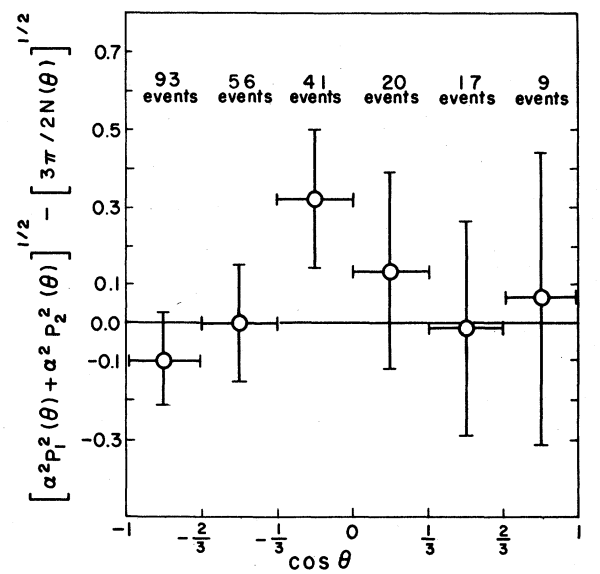

FIG. 1. Magnitude of the Λ decay asymmetry in the production plane, minus $[3\pi/2N(\theta)]^{\frac{1}{2}}$, the mean value expected from statistical fluctuations alone, plotted versus θ, the hyperon c.m. production angle. The plotted errors are the rms fluctuations $\pm[(2-\pi/2)3/N(\theta)]^{\frac{1}{2}}$.

tems might be expected to be "preferred" in the sense that the polarization in the production plane would not cancel vectorially in averaging over θ.

The results are summarized in Table I. No statistically significant average polarization in the production plane is apparent in any of the coordinate systems.[11] (This result was, of course, guaranteed by the negative result from the preceding "coordinate-invariant" analysis.)

We now adopt the hypothesis that parity is not conserved in production in order to determine an upper limit to the parity-nonconserving amplitude. In the notation of Drell et al.[5] and Lee et al.,[8] the production matrix element (M.E.)

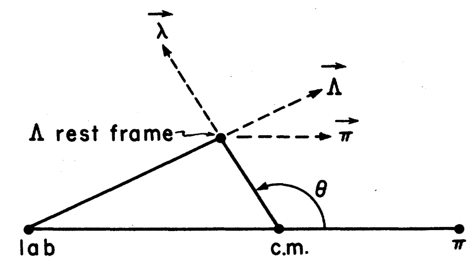

FIG. 2. Mnemonic (nonrelativistic) diagram in velocity space. $\vec{\pi}$, $\vec{\Lambda}$, and $\vec{\lambda}$ are unit vectors, referring to the direction of the incident π with respect to the center of mass, the Λ with regard to the laboratory frame, and the Λ with regard to the c.m., all as seen in the Λ rest frame. See also reference 9.

may be written

$$\text{M.E.} = a + b\cos\theta + ic\sin\theta\,\vec{\sigma}\cdot\vec{n} + d\vec{\sigma}\cdot\vec{\pi},$$

where d is the parity-nonconserving amplitude. Then, in the "π - c.m." coordinate system (Fig. 2 and Table I), we have

$$I(\theta)P_n(\theta) = 2\text{Im}c^*(a + b\cos\theta)\sin\theta,$$

$$I(\theta)P_\pi(\theta) = 2\,\text{Re}d^*(a + b\cos\theta),$$

$$I(\theta)P_2(\theta) = 2\,\text{Re}d^* c\sin\theta,$$

$$I(\theta) = |a + b\cos\theta|^2 + |c\sin\theta|^2 + |d|^2.$$

After averaging over θ we have

$$\langle IP_n\rangle = (\pi/2)\,\text{Im}c^* a, \quad (3)$$

$$\langle IP_\pi\rangle = 2\,\text{Re}d^* a, \quad (4)$$

$$\langle IP_2\rangle = (\pi/2)\,\text{Re}d^* c, \quad (5)$$

$$\bar{I} = |a|^2 + |b|^2/3 + 2|c|^2/3. \quad (6)$$

Since $\bar{P}_n$ is observed to be large, c and a must both be nonzero, and their phase difference cannot be 0° or 180°. Therefore, $\bar{P}_\pi$ and $\bar{P}_2$ cannot both vanish, unless $|d|$ is 0.

If we eliminate the phase of d from Eqs. (3),

Table I. Polarization components averaged over hyperon c.m. production angle. Here $\vec{n}$ is a unit vector in the direction $\vec{P}(\pi \text{ incident}) \times \vec{P}(\text{hyperon})$. The standard deviations on all $\alpha\vec{P}_{1,2,3}$ are $(3/236)^{\frac{1}{2}} = 0.113$. Prob. $(\chi_{1,2}^{\ 2}) = \exp\{-[\alpha^2\bar{P}_1^{\ 2} + \alpha^2\bar{P}_2^{\ 2}]\,236/6\}$ = the probability of getting a χ^2 as large as or larger than that observed, if the true values are $\bar{P}_1 = \bar{P}_2 = 0$.

Coord. system	Axis No. 3	Axis No. 1	Axis No. 2	$\alpha\bar{P}_3$	$\alpha\bar{P}_1$	$\alpha\bar{P}_2$	Prob. $(\chi_{1,2}^{\ 2})$
π - c.m	$\vec{n}$	$\vec{\pi}$	$\vec{n}\times\vec{\pi}$	0.55	-0.13	+0.15	0.21
Λ - c.m.	$\vec{n}$	$\vec{\lambda}$	$\vec{n}\times\vec{\lambda}$	0.55	+0.087	+0.068	0.62
Λ - lab	$\vec{n}$	$\vec{\Lambda}$	$\vec{n}\times\vec{\Lambda}$	0.55	-0.046	+0.18	0.26

(4), and (5) and insert our results from Table I, we obtain

$$|d|^2/|a|^2 = \{\bar{P}_2^{\,2} + [(\pi/4)|c/a|\bar{P}_\pi]^2 - 2\cos\phi \times (\pi/4)|c/a|\bar{P}_\pi \bar{P}_2\}/\bar{P}_n^{\,2}$$
$$= 0.0744 + 0.0344\,|c/a|^2 + 0.101\cos\phi\,|c/a|,$$

where ϕ is the phase of a relative to c.

Because of the result that $|d|$ is small, it turns out that the inclusion of d does not substantially change the solutions for a, b, and c obtained by setting $d = 0$. There are several such solutions.[8] The one that yields the largest value for $|d|$ has $|c/a| = 1.42$, $d = 46°$, to give $|d|^2/|a|^2 = 0.24 \pm 0.27$.

In terms of integrated cross sections, we find[8]

$$\sigma(S\text{ wave})/\sigma(\text{Total}) = |a|^2/[|a|^2+|b|^2/3+2|c|^2/3] = 0.28 \pm 0.16,$$

so that

$$\sigma(\text{Parity not conserved})/\sigma(\text{Total}) = 0.07 \pm 0.08.$$

We wish to thank Luis W. Alvarez for his continued interest and guidance.

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†This work was reported at the 1958 Annual International Conference on High-Energy Physics, at CERN.

1 Crawford, Cresti, Good, Gottstein, Lyman, Solmitz, Stevenson, and Ticho, Phys. Rev. 108, 1102 (1957).

2 Eisler, Plano, Prodell, Samios, Schwartz, Steinberger, Bassi, Borelli, Puppi, Tanaka, Woloschek, Zoboli, Conversi, Franzini, Mannelli, Santagelo, Silvestrini, Brown, Glaser, Graves, and Perl, Phys. Rev. 108, 1353 (1957).

3 N. Tanner, Phys. Rev. 107, 1203 (1957); D. H. Wilkinson, Phys. Rev. 109, 1603 (1958).

4 V. G. Soloviev, Joint Institute for Nuclear Research, U.S.S.R., Report P-147, 1958 (unpublished).

5 Drell, Frautschi, and Lockett (to be published).

6 For instance, strangeness conservation forbids the exchange of a single K meson between two nucleons. On the other hand, the (allowed) exchange of two K mesons should lead to comparatively short-range forces, which might play only a small role in low-energy nuclear forces. Further, under the suggestive hypothesis that PC invariance holds for the strong interactions (as it seems to for the weak), then for pion-nucleon forces charge independence (CI) implies C invariance and hence P invariance. But in the nucleon-hyperon-K meson interaction, CI does not imply C invariance, since the (K^+, K^0) doublet is distinct from its C conjugate doublet (K^-, $\bar{K}^0$). Thus the combination CI plus CP invariance does not imply P invariance for strange particles.[5]

7 This is true only if Reaction (1) does not proceed through parity-doublet formation. There are at present no theoretical or experimental reasons for believing that parity doublets exist. See, for instance, Eisler, Plano, Samios, Schwartz, and Steinberger, Phys. Rev. 107, 324 (1957).

8 Results of analysis of the same 236 events, presented at the 1958 Annual International Conference on High-Energy Physics at CERN, and to be published. The analysis assumes Λ spin $\frac{1}{2}$, parity conservation in the production, and s and p waves only in the $K\Lambda$ system. The notation is that of Lee, Steinberger, Feinberg, Kabir, and Yang, Phys. Rev. 106, 1367 (1957).

9 The χ^2 test applies only to normally distributed variables, i.e., to a_1 and a_2, not to $a = (a_1^{\,2} + a_2^{\,2})^{\frac{1}{2}}$. Then

$$\chi^2 = \sum_{j=1}^{6} [a_1^{\,2}(j) + a_2^{\,2}(j)]\,N(j)/3$$
$$= (1/3)\,[94(0.131)^2 + 56(0.292)^2 + 41(0.662)^2 + 20(0.623)^2 + 17(0.514)^2 + 9(0.787)^2]$$
$$= 14.1.$$

10 Figure 2 is mnemonic only, because of the nonlinearity of velocity addition in the Lorentz transformation (LT). The unit vectors $\vec{\pi}$, $\vec{\Lambda}$, and $\vec{\lambda}$ are obtained by transforming measured laboratory-system quantities first to the c.m., then to the Λ frame. Because of the LT nonlinearity, these differ by a (small) rotation from the corresponding directions obtained by transforming directly from the lab frame to the Λ frame. See, for instance, Henry Stapp, University of California Radiation Laboratory Report UCRL-8096, December 1957 (unpublished).

11 One can compare our $\alpha\bar{P}_1(\Lambda\text{-lab}) = -0.046 \pm 0.11$ with results of numerous cosmic-ray and Cosmotron cloud chamber observations on Λ decays from Λ's produced in complex nuclei. These experiments have indicated a front-back decay asymmetry with regard to the Λ line of flight. [See, for instance, Blumenfeld, Chinowsky, and Lederman, Nuovo cimento 8, 296 (1958), and references given by them.] These experiments are not conclusive. Although all experiments agree on the sign of the effect, it is of doubtful validity to combine the cosmic-ray and Cosmotron statistics, since the production mechanisms differ, and presumably could lead to opposite polarizations.

K^+ MESON-NUCLEON SCATTERING PHASE SHIFT ANALYSIS*

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Nuclear emulsion data on K^+-meson interactions have recently been analyzed in terms of K^+-meson real scattering amplitudes.[1] We feel