of the theory. It has been shown by Schwinger[6] that a three-dimensional covariant theory will be invariant under the group of proper, orthochronous Lorentz transformation, if the energy density, $T^{00}(x)$, obeys the equal-time commutator relation

$$-i[T^{00}(x), T^{00}(x')] = -[T_k^{\;0}(x) + T_k^{\;0}(x')]\partial_k \delta(\vec{x}-\vec{x}').$$

The energy density operator in our theory is

$$T^{00}(x) = \tfrac{1}{2}\psi\alpha^k (1/i) D_k \psi + \tfrac{1}{2} m\psi\gamma^0 \psi + \tfrac{1}{4} F_{kl} F_{kl}$$

$$+ (e/8m)(\psi\gamma^0 \sigma_{kl} q\psi) F_{kl} + \tfrac{1}{2} F^{0k} F^{0k}.$$

The Schwinger relation can be verified either by means of the technique of extended operators[7] or simply by direct computation. This completes the verification of the Lorentz invariance of our interacting system.

I wish to express my sincere gratitude to Professor Julian Schwinger for his guidance and encouragement. It is my pleasure to thank T. M. Yan for helpful discussions.

*Work supported in part by the U. S. Air Force Office of Scientific Research under Contract No. AF 49(638)-1380.

†John Parker Fellow.

[1]F. Gürsey and L. A. Radicati, Phys. Rev. Letters 13, 173 (1964); A. Pais, ibid. 13, 175 (1964); F. Gürsey, A. Pais, and L. A. Radicati, ibid. 13, 299 (1964); B. Sakita, ibid. 13, 643 (1964); Phys. Rev. 136, B1759 (1964); A. Salam, R. Delbourgo, and J. Strathdee, Proc. Roy. Soc. (London) A284, 146 (1965).

[2]G. S. Guralnik and T. W. B. Kibble, Phys. Rev. 139, B712 (1965).

[3]Throughout this paper we use the following notations: $g_{\mu\nu} = (-1, 1, 1, 1)$; all Greek indices $\mu, \nu, \cdots$ vary from 0 to 3 and all Latin indices $i, j, \cdots$ vary from 1 to 3. Repeated indices are to be summed over; the γ matrices are chosed as γ^0 = antisymmetric and imaginary, $\alpha^0 = 1$, $\gamma_k = \gamma^0\alpha_k$ = symmetric and imaginary, $\{\gamma_\mu, \gamma_\nu\} = -2g_{\mu\nu}$, $\sigma_{\mu\nu} = \frac{1}{2}i[\gamma_\mu\gamma_\nu]$, $\gamma_5 = \gamma^0\gamma^1\gamma^2\gamma^3$. The dots between the field operators indicate that the latter are symmetrically (or antisymmetrically) multiplied.

[4]T. D. Lee, Phys. Rev. 140, B967 (1965).

[5]For the calculation of stress tensor see, e.g., J. Schwinger, Phys. Rev. 82, 914 (1951); 91, 713 (1953).

[6]J. Schwinger, Phys. Rev. 127. 324 (1962).

[7]J. Schwinger, Nuovo Cimento 30, 278 (1963); Phys. Rev. 132, 1317 (1963).

$K_2^{\;0}p$ INTERACTIONS AT LOW MOMENTUM*

John A. Kadyk, Yona Oren, Gerson Goldhaber, Sulamith Goldhaber,† and George H. Trilling
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received 25 July 1966)

An analysis is given of about 1200 $K_2^{\;0}p$ interactions of the types $\Lambda^0\pi^+$, $\Sigma^0\pi^+$, and $K_1^{\;0}p$ at a mean $K_2^{\;0}$ momentum of 300 MeV/c. The relation between these reactions and the scattering lengths from K^+ and K^- experiments is discussed, and a substantial P wave is reported in the $\Lambda^0\pi^+$ reaction.

We have studied the $K_2^{\;0}p$ interactions around 300 MeV/c.[1] As pointed out by Biswas,[2] a measurement of the ratio R of $K_1^{\;0}$ to hyperon production in the $K_2^{\;0}p$ reaction can resolve the ambiguity between the solutions for the complex zero-range scattering lengths obtained in low-energy K^-p experiments.[3-5] The latest status of these solutions is that Kim obtained a unique answer[4] in accord with the $\frac{1}{2}^-$ interpretation for the $Y^*(1405)$, while Sakitt et al.[5] obtained two ambiguous solutions. Our determination of R shows that the only acceptable solution is the one consistent with the Dalitz-Tuan interpretation of the $Y_0^*(1405)$ as a $\bar{K}N$ virtual bound-state resonance.[6] Thus, while the negative-strangeness amplitudes in the $K_2^{\;0}p$ interactions are purely in the isospin $T = 1$ state, our results coupled with those from K^+p, K^+d,[7] and K^-p experiments determine the spin and parity of the $T = 0$ resonance $Y_0^*(1405)$ to be $\frac{1}{2}^-$. Furthermore, we find a considerable amount of P-wave amplitude to be present in the reaction $K_2^{\;0} + p \to \Lambda^0 + \pi^+$, in which a strong forward-backward asymmetry is observed in the production distributions. A possible source of this P-wave amplitude seems to be the presence of the $Y_1^*(1385)$ resonance, which lies below the $K\bar{N}$ threshold.

Experimental technique.—The experimental layout at the Bevatron is illustrated in Fig. 1. A K^+ beam (~800 MeV/c) was produced from a target placed in the external proton beam

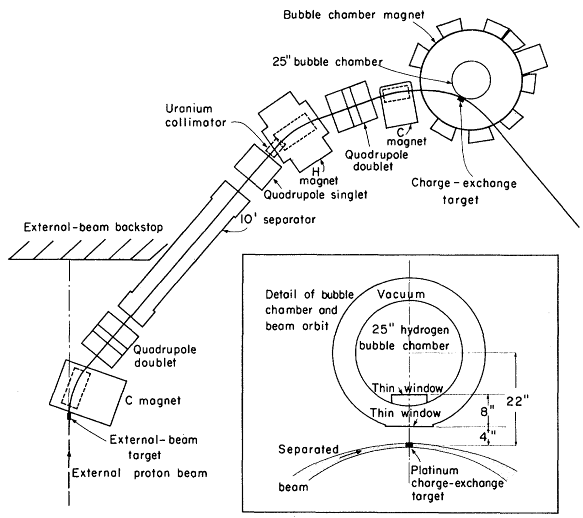

FIG. 1. Experimental arrangement at the Bevatron, with detail of 25-inch hydrogen bubble chamber and charge-exchange target.

of the Bevatron. The K^+ beam was focused to a small spot on a charge-exchange target near the 25-inch hydrogen bubble chamber[8] creating the $K_2{}^0$ beam. Pions and protons accompanying the K^+ beam were deflected vertically by an electrostatic separator so as to miss the charge-exchange target, orbit through the bubble-chamber fringe field, and be stopped far enough away to cause no appreciable background. With 1000 K^+ particles incident on the target, about one $K_2{}^0$ entered the chamber each pulse, and a $K_2{}^0$ decay or interaction occurred, on the average, every 17 pictures. To date about 1200 interactions that lead to a visible Λ^0 or $K_1{}^0$ decay have been analyzed. This represents approximately half of our available sample.

The interactions considered here are[9] the following:

$$K_2{}^0+p\to K_1{}^0+p,\quad K_1{}^0\to\pi^++\pi^-\quad 403 \text{ events},\tag{1}$$

$$\to\Lambda^0+\pi^+,\quad \Lambda^0\to\pi^-+p\quad 481 \text{ events},\tag{2}$$

$$\to\Sigma^0+\pi^+,\quad \Sigma^0\to\gamma+\Lambda^0,$$

$$\Lambda^0\to\pi^-+p\quad 332 \text{ events}.\tag{3}$$

Of the various potential sources of scanning bias in the analysis of these reactions, nearly all are of the order of a few percent at most, and have been corrected for. The ambiguities between reactions are quite small. Because of the low energies involved, the $K_1{}^0$ and Λ^0 decays can be recognized at the scan table in nearly every instance, and, in combination with kinematic fitting, we obtain a unique identification of the decay particle. For Λ^0 and Σ^0 production, the events look the same at the scan table, but there is only a 3% overlap after the kinematic fitting. From our data we have evaluated the ratio R given by

$$R=\frac{\sigma(K_1{}^0p)}{\sigma(Y)}=\frac{\sigma(K_1{}^0p)}{\sigma(\Lambda^0\pi^+)+2\sigma(\Sigma^0\pi^+)}.\tag{4}$$

In the S-wave zero-effective-range approximation, the relevant cross sections are related to the strangeness $=+1$, $T=0$, and 1 scattering lengths a_0 and a_1 which are real,[7] and the strangeness $=-1$, $T=1$, complex scattering length $\bar{A}_1=\bar{a}_1+i\bar{b}_1$ by[2]

$$\sigma(K_1{}^0p)=\pi\left|\tfrac{1}{2}\left(\frac{a_0}{1-ika_0}+\frac{a_1}{1-ika_1}\right)-\frac{\bar{A}_1}{1-ik\bar{A}_1}\right|^2\tag{5}$$

and

$$\sigma(Y)=\frac{2\pi}{k}\,\frac{\bar{b}}{|1-ik\bar{A}|^2},\tag{6}$$

where k is the momentum of the $K_2{}^0$ in the overall center of mass. This ratio is a function of $K_2{}^0$ energy, and because of interference in the $K_1{}^0p$ reaction between the strangeness +1

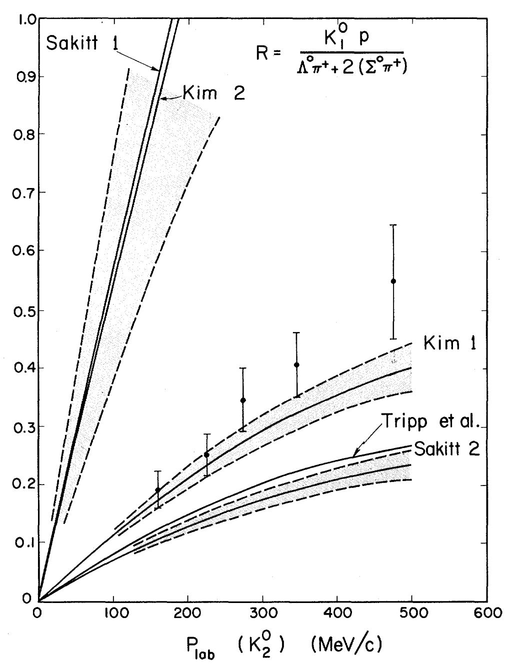

FIG. 2. R vs $K_2{}^0$ momentum. The uncertainties in the predicted values of R are indicated by the shaded bands based on the quoted errors in the K^- and K^+ experiments. The data points are the result of the present experiment.

and −1 scattering amplitude, it turns out to be quite sensitive to the differences between the two K^-p solutions. An earlier determination of R was made by Luers et al.[10] on the basis of 111 events. For their determination in the lowest momentum range, they obtained $R=0.4$ to 0.9 at $P(K_2^0)=230$ MeV/c, which lies about midway between the two solutions, and thus could not resolve the ambiguity.

We have evaluated the ratio R in five momentum intervals. The result is given in Fig. 2 and Table I, along with the predictions based on the scattering-length determination from the experiments of Sakitt et al.,[5] and of Kim[4] at low energy, and from Tripp at somewhat higher energies.[11] From Fig. 2 we conclude that the correct set of solutions is the one giving the smaller values for R.[12] This is the set that predicts a $\bar{K}N$ bound state near 1405 MeV. We further conclude that our data agree well with the prediction for R based upon the $T=1$ scattering lengths from Kim's experiment, but differ considerably from that based upon the preferred solution of Sakitt et al.[5] These predictions also depend upon the strangeness $=+1$ scattering lengths, which are assumed from previous K^+ experiments. It should be pointed out that above 250 to 300 MeV/c one may expect a breakdown of the zero-effective-range approximation and that the theoretical predictions in this region may not be quite correct.

In the K^-p experiments below 300 MeV/c, there has been no need to assume amplitude other than S wave in order to explain the observed distributions.[3-5,11] In Fig. 3 we show the variation of the $\Lambda^0\pi^+$ angular distribution with momentum (see also Table I). At the lowest momentum there is only a small amount of P wave compared with S wave (about 15% in the amplitude). As the momentum increases, a strong backward peak appears in the distributions, indicating the presence of a larger amount of P-wave amplitude (40% in the amplitude). Table I gives the results of fitting these curves to Legendre polynomials. Expansions to orders higher than second do not improve the fits significantly except perhaps in the 250- to 300-MeV/c region. The presence of such a substantial amount of P wave in the $T=1$ state may be explained in terms of the $Y_1^*(1385)$ resonance, which lies 50 MeV below the $\bar{K}N$ threshold. The high-energy tail of that resonance extends into the energy region being studied in this experiment. We have calculated the expect-

Table I,[a] R, ϵ,[b] and coefficients in Legendre-polynomials expansion to fit production angular distributions.

Range of K_2^0 Momentum (MeV/c)	Av. K_2^0 Momentum (MeV/c)	Observed No. of Events	R	ϵ	Fit to $\Lambda^0\pi^+$ distribution (Fig. 4) A_1	A_2	A_3	A_4	Confidence level of fit (%)	Fit to K_1^0p distributions A_1	A_2	A_3	Confidence level of fit (%)
0 to 200	160	261	0.19±.03	0.35±.03	-0.52±.15				76	0.36±.33			31
200 to 250	225	304	0.25±.04	0.36±.03	-0.99±.14	0.49±.21			34	-0.41±.32			81
250 to 300	275	224	0.35±.05	0.32±.04	-1.07±.17	-0.19±.25	0.40±.32	-1.06±.63	5	-0.13±.31			24
300 to 400	340	277	0.40±.05	0.34±.04	-0.94±.18	0.61±.25			13	-0.53±.20			94
Above 400	460	150	0.55±.10	0.41±.06	-1.18±.23	1.02±.27			25	-1.12±.22	0.68±.33	-1.15±.41	77

a. In this table R, ϵ, and the coefficients A_1, A_2, A_3, and A_4 are based upon the corrected number of events. The coefficients have been normalized to a constant term $A_0 = 1$. The Σ^0 production distributions are all consistent with isotropy.

b. $\epsilon = \sigma(\Lambda^0)/[\sigma(\Lambda^0)+2\sigma(\Sigma^0)]$.

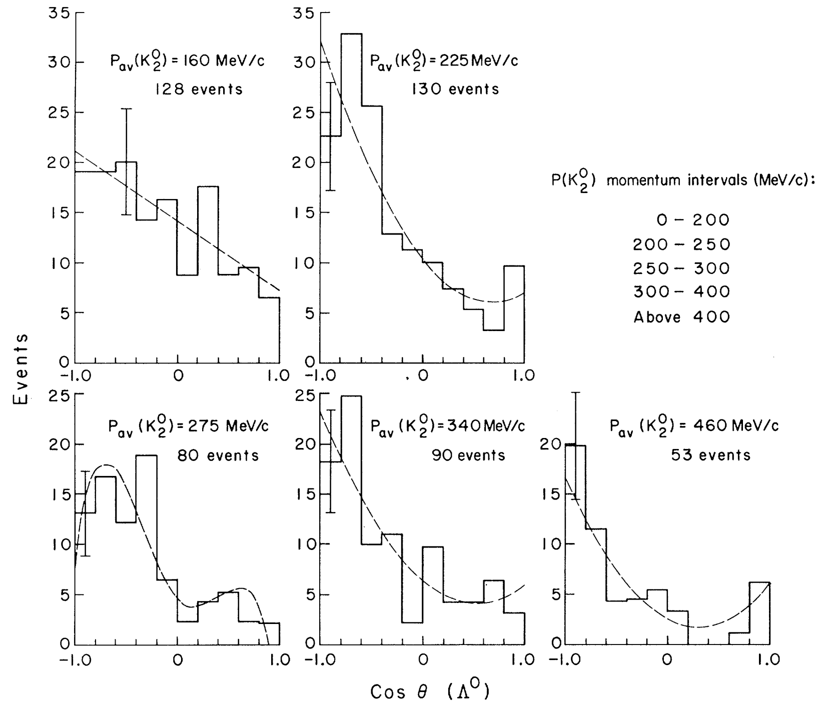

FIG. 3. Corrected c.m. angular distributions for $\Lambda^0\pi^+$ production from the reaction $K_2^0+p\rightarrow\Lambda^0+\pi^+$. The production angle is defined here to be the direction of the Λ^0 relative to the K_2^0 in the over-all center of mass. The total number of events is 481. The dashed curves represent the best fit to the data, as given in Table I.

ed amount of P wave from the $Y_1^*(1385)$, using the Breit-Wigner formula with energy-dependent widths, and find substantial agreement with the observed asymmetry, except in the lowest momentum interval. Here the predicted P-wave amplitude is somewhat in excess of that observed.[13] We observe no significant Λ^0 polarization, which implies that the S- and P-wave amplitude vectors must be relatively real.

The angular distributions for K_1^0p production are much more isotropic, and can be fitted to a linear function of $\cos\theta$, except for the highest momentum region (see Table I). One would expect less asymmetry to appear in this reaction than for $\Lambda^0\pi^+$ for two reasons: (1) The P-wave amplitude is still smaller, since the phase-space and barrier-penetration factors are more inhibiting than for the Λ^0 channel and (2) the P-wave amplitude vector resulting from the tail of the $Y_1^*(1385)$ is expected to be approximately real and negative, while the S wave is largely imaginary due to the strong absorption. As a consequence, the two vectors are nearly out of phase.

We wish to thank the Bevatron staff, as well as Bob Watt, Glenn Eckman, and the crew of the 25-inch bubble chamber for the help given to make this experiment possible. We also wish to thank Dr. J. L. Brown for help in the early stages of this experiment.

---

*Work done under the auspices of the U. S. Atomic Energy Commission.

†Deceased. John S. Guggenheim Fellow.

[1]J. A. Kadyk, Y. Oren, R. Brower, J. L. Brown, I. Butterworth, G. Goldhaber, S. Goldhaber, J. McNaughton, B. C. Shen, and G. H. Trilling, Bull. Am. Phys. Soc. 11, 37 (1966).

[2]N. N. Biswas, Phys. Rev. 118, 886 (1960).

[3]W. E. Humphrey and R. R. Ross, Phys. Rev. 127, 1305 (1962).

[4]J. K. Kim, Phys. Rev. Letters 14, 29 (1965).

[5]M. Sakitt, T. B. Day, R. G. Glasser, N. Seeman, J. Friedman, W. E. Humphrey, and R. R. Ross, Phys. Rev. 139, B719 (1965).

[6]R. H. Dalitz and S. F. Tuan, Ann. Phys. (N.Y.) 10, 307 (1960).

[7]S. Goldhaber et al., Phys. Rev. Letters 9, 135 (1962); V. J. Stenger, W. E. Slater, D. H. Stork, H.K. Ticho, G. Goldhaber, and S. Goldhaber, Phys. Rev. 134, B1111 (1964).

[8]The charge-exchange target subtends ±2 deg hori-

zontally, and ±0.4 deg vertically at the center of the chamber. The direction of the $K_2{}^0$ line of flight is computed from the known target and interaction positions, and this information is used in the fitting procedure.

[9]In addition, reactions $\Sigma^+ + \pi^0 (\Sigma^+ \to \pi^+ + n)$ and $K^+ n$ have been scanned for, but these events have not been fully analyzed.

[10]D. Luers, I. Mittra, W. Willis, and S. Yamamoto, Phys. Rev. Letters 7, 255 (1961).

[11]M. B. Watson, M. Ferro-Luzzi, and R. D. Tripp, Phys. Rev. 131, 2248 (1963). Above 300 MeV/c, there is evidence for an asymmetry in the angular distribution in the $\Lambda^0 \pi^0$ channel, in qualitative agreement with the asymmetry reported in this Letter.

[12]There is additional evidence to help resolve the ambiguity in favor of the Dalitz-Tuan interpretation. Specifically, in the $K^- p$ experiment of Ref. 11 in the momentum range 300 to 500 MeV/c, interference was observed between the $Y_0{}^*(1520)$ resonance and the S-wave background. The continuity argument of T. Akiba and R. H. Capps, Phys. Rev. Letters 8, 457 (1963), then implied that the relative phase of the isospin-0 and -1 channels was such that only one set of scattering lengths was possible. In addition, recent $K^- p$ charge-exchange experiments [G. S. Abrams and B. Sechi-Zorn, Phys. Rev. 139, B454 (1965) and W. Kittel, G. Otter, and I. Wacok, Phys. Letters 21, 349 (1966)] are consistent with only this set of solutions, as is the experiment by E. F. Beall, G. Sayer, T. V. Devlin, P. Shephard, and J. Solomon, Bull. Am. Phys. Soc. 11, 326 (1966).

[13]A phase-shift analysis, using both polarization data and the angular distributions, is currently in progress, and will include many more events than the present sample.

EXPERIMENTAL TEST OF TIME-REVERSAL INVARIANCE IN $\Sigma^0 \to \Lambda^0 + e^+ + e^-$

R. G. Glasser* and B. Kehoe*
University of Maryland, College Park, Maryland

and

P. Engelmann and H. Schneider
Institute for High Energy Physics, University of Heidelberg, Heidelberg, Germany

and

L. E. Kirsch†
Columbia University, New York, New York

(Received 1 April 1966)

Bernstein, Feinberg, and Lee[1] and S. Barshay[2] have suggested that the observed violation of time-reversal invariance (T) in $K_2{}^0$ decays[3] could be accounted for by the existence of a T-nonconserving electromagnetic interaction of the strongly interacting particles. This suggestion has been supported by recent evidence from the charged decay of the η^0.[4] Such an interaction could also give rise to a polarization of the Λ^0 in the Dalitz decay of an unpolarized Σ^0

$$\Sigma^0 \to \Lambda^0 + e^+ + e^-. \tag{1}$$

The polarization direction would be expected to be along the normal to the decay plane of process (1), defined by

$$\vec{\mathrm{N}} = \hat{p}_\Lambda \times (\hat{p}_+ + \hat{p}_-), \tag{2}$$

where $\hat{p}_\Lambda$, $\hat{p}_+$, and $\hat{p}_-$ are unit vectors along the directions of the Λ^0, the positron, and the electron in the Σ^0 center-of-mass system.

We have looked for such an effect in 907 events of this type used in our determination of the relative parity of the Σ and Λ.[5,6]

In the one-photon exchange approximation, a polarization along the normal (2) requires a violation of T but is consistent with parity conservation and with charge conjugation invariance of the electromagnetic interactions of the leptons. Polarization of the Λ^0 can also arise from the decay of polarized Σ^0 hyperons. In these experiments, the Σ^0's are thought to originate from interactions at rest of K^- mesons or Σ^- hyperons on unpolarized protons which will produce unpolarized Σ^0's. In any case, in the one-photon approximation, the direction of the normal (2) is independent of the Σ^0 spin; hence, a Λ polarization correlated with the Σ^0 spin direction will not affect our results.

The presence of a T-nonconserving interaction would, in general, give rise to a nonzero mean value for the quantity $\hat{N} \cdot \hat{p}_p$, where $\hat{N}$ is a unit vector in the direction of the normal