

⁴In a sample representing one-fourth of the film reported here, the requirement that one of the protons had to stop with a range ≤ 15 cm was removed. The results agree within statistics with those reported here.

⁵Events were accepted for analysis which fit the following criteria: (a) $\chi^2 \leq 6$ for the hypothesis $\pi^+ + d \rightarrow p + p + \pi^+ + \pi^- + \pi^0$. (b) $\chi^2 \geq 25$ for the hypothesis $\pi^+ + d \rightarrow p + p + \pi^+ + \pi^-$. (c) If the nonstopping proton had a momentum ≥ 700 Mev/c, where it becomes difficult to differentiate a proton from a π^+ by ionization in this chamber, then the χ^2 had to be greater than 15 for the hypothesis $\pi^+ + d \rightarrow p + n + \pi^+ + \pi^+ + \pi^-$, which is another background reaction under these circumstances.

⁶The ideogram was calculated in units of mass squared since our experimental errors are Gaussian in this rep-

resentation. Each event was given a constant-area Gaussian distribution.

⁷M. M. Block, Phys. Rev. 101, 796 (1956); P. Srivastava and G. Sudarshan, Phys. Rev. 110, 765 (1958).

⁸R. Hofstadter and R. Herman, Phys. Rev. Letters 6, 293 (1961); R. M. Littauer, H. F. Schopper, and R. R. Wilson, Phys. Rev. Letters 7, 141 (1961).

⁹S. Fubini, Proceedings of the 1961 Conference on Elementary Particles, Aix-en-Provence (to be published); P. T. Matthews, *ibid.*; G. Breit, Proc. Natl. Acad. Sci. U. S. 46, 746 (1960); Y. Fujii, Progr. Theoret. Phys. (Kyoto) 21, 232 (1959).

¹⁰G. Feldman, T. Fulton, and K. C. Wali (private communication); see also J. Sakurai, Phys. Rev. Letters 7, 355 (1961).

EXPERIMENTAL STUDY OF THE K_{e3}^+ DECAY INTERACTION*

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Although the $V-A$ theory has been used with considerable success to explain the observed features of the weak decays of nucleons, pions, and muons, only a few experimental tests have been made to determine if the same couplings apply to the leptonic decay modes of strange particles. Insofar as the two-body modes of K^+ mesons are concerned, the experimental upper limit to the K_{e2}^+ ($K^+ \rightarrow e^+ + \nu$) branching ratio (namely about 1%)¹ is certainly compatible with the value of 1.5×10^{-5} expected from the $V-A$ coupling.² The interpretation of various features of the K_{e3}^+ ($K^+ \rightarrow e^+ + \pi^0 + \nu$) and $K_{\mu 3}^+$ ($K^+ \rightarrow \mu^+ + \pi^0 + \nu$) decay modes in terms of possible couplings has been the object of considerable theoretical work. Pais and Treiman³ have pointed out that the K_{e3}^+ mode leads to especially simple predictions and have obtained the following distribution functions of the pion momentum and pion-electron angular correlation:

For vector coupling,

$$F(P, \theta) dP d \cos \theta = \frac{P^4 (W^2 - P^2)^2 \sin^2 \theta |f_v|^2}{E (W + P \cos \theta)^4} dP d \cos \theta; \quad (1a)$$

for scalar coupling,

$$F(P, \theta) dP d \cos \theta = \frac{P^2 (W^2 - P^2)^2 |f_s|^2}{E (W + P \cos \theta)^2} dP d \cos \theta; \quad (1b)$$

for tensor coupling,

$$F(P, \theta) dP d \cos \theta = \frac{P^4 (W^2 - P^2)^2 (P + W \cos \theta)^2 |f_t|^2}{EM^2 (W + P \cos \theta)^4} \times dP d \cos \theta, \quad (1c)$$

where P and E are the pion momentum and total energy; M is the K -meson mass; $W = M - E$; θ is the angle between the pion and electron momenta; and the quantities f_v , f_s , and f_t are functions that depend only on the total pion energy, E . The labels vector, scalar, etc., are appropriate to a pseudoscalar K^+ meson and should be replaced by axial vector, pseudoscalar, etc., for a scalar K^+ meson, with no change in the functions (1). Thus the vector, axial-vector coupling leads to the distribution given in Eq. (1a), independently of the K -meson parity. It is clear that for any assumed form factors f_v , f_s , and f_t , the expressions (1) determine the energy spectra and angular correlations of any of the three secondaries

of the decay. Furuichi *et al.* have calculated the electron energy distributions on the assumption that the energy dependence of the form factors can be neglected,⁴ but the experimental data on this point are too meager to allow a conclusive comparison with the theory.⁵ Recently Luers *et al.* have studied the K_2^0 modes, $K_2^0 \rightarrow e^\pm + \pi^\mp + \nu$, in a hydrogen bubble chamber,⁶ and have concluded from both the pion energy spectra and the electron energy spectra for fixed pion energy that their data are in good agreement with the vector coupling.

In this Letter we present the results of a study of K_{e3}^+ decay events obtained in an exposure of the 21-liter xenon bubble chamber to a separated K^+ beam at the Bevatron. We identify this decay mode by observing the large radiative energy loss of the charged secondary in the xenon. Our efficiency for recognizing electrons in this way is 90%.⁷ In all events used in our analysis, both gamma rays from the π^0 meson convert into electron pairs in the xenon, and these conversion points as well as the K^+ decay points lie within appropriate fiducial volumes in the chamber. With these requirements, we have obtained from the fraction of our film so far processed a sample of 175 events. The quantities measured in each decay are the two gamma-ray directions and the electron direction.

To investigate the pion momentum spectrum, we have studied the distribution of the opening angle ϕ between the two decay gamma rays. This angle is closely correlated with the pion momentum, and its distribution is easily calculated for any given pion energy spectrum. If one neglects the energy dependence of the form factors, the pion momentum distributions appropriate to the three couplings can be obtained by integration of Eq. (1) over θ ; these are shown in Fig. 1(a). The corresponding ϕ distributions, calculated with measurement errors of 2 deg folded in, are shown in Fig. 1(b) together with a histogram representing our experimental data.

A χ^2 test shows good agreement between the data and the vector distribution and rules out the other hypotheses with a confidence level of better than 99.9%. We have investigated the possible effects of biases on these conclusions by comparing the expected and observed ϕ distributions for π^0 mesons from the $K_{\pi 2}^+$ ($K^+ \rightarrow \pi^+ + \pi^0$) decay mode. This comparison indicates that any biases are small and have no significant effect on the above results.

This test, though very suggestive of the validity of the vector hypothesis, is not absolutely con-

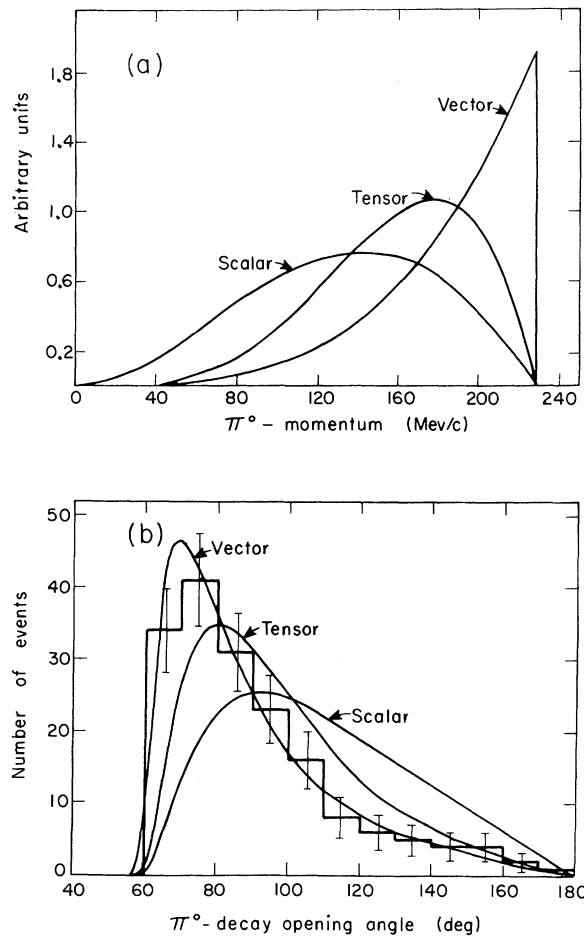


FIG. 1. (a) Pion momentum spectra for the various couplings (constant form factors assumed). (b) Experimental histogram and theoretical distributions (constant form factors assumed) for the π^0 -decay opening angle ϕ .

clusive because of the possibility that a form factor with a strong energy dependence can cause the tensor or scalar couplings to lead to the observed ϕ distribution. This ambiguity can be resolved, at least in principle, by a study of the pion-electron angular correlation.

If we require that the predicted π^0 momentum spectrum for each of the three hypotheses agrees with the experimental observations, then the form factors are uniquely determined, at least to the statistical accuracy of the data, and the expected pion-electron angular correlations can be calculated from Eq. (1) by integrating over all π^0 energies. It must be emphasized that the predicted correlations so obtained are independent of a priori assumptions about the energy dependence of

the form factors and, when compared with experiment, provide an absolute test of the validity of each of the possible couplings. We have investigated the pion-electron correlation by studying the distribution of $\cos\theta'$, θ' being the angle between the electron direction and the bisector of the angle ϕ . The direction of this bisector is closely related to the π^0 direction. We have computed the distributions of $\cos\theta'$ expected for each of the various couplings by a Monte Carlo technique. In this calculation the decay configurations were selected in accordance with Eq. (1) and π^0 decay kinematics, with form factors so chosen as to lead to the π^0 momentum spectrum given by the vector curve in Fig. 1(a). This choice of form factors implies a momentum dependence for $|f_S|^2$ ($|f_T|^2$) given by the ratio between the vector and scalar (tensor) curves of Fig. 1(a). This procedure is justified by the excellent agreement between the experimental histogram and the vector curve in Fig. 1(b). The distributions of $\cos\theta'$, predicted by Monte Carlo calculations of 1200 events for each coupling, are shown in the three histograms of Fig. 2. The experimental data, also shown in Fig. 2, are in good agreement with either the vector or the scalar hypothesis, but disagree with the tensor hypothesis with a confidence level of better than 99.9%. The rather poor discrimination between vector and scalar angular correlations arises mainly from the fact that the pion energy distribution is highly peaked at the upper end, in which region the differences in correlations between the various couplings are lessened because of the rapidly varying ($W+P\cos\theta$) phase-space factors appearing in the denominator of Eq. (1).

If we then take the coupling to be vector, we can set rough limits on the energy dependence of the form factor f_V . If we assume the form $f_V \sim 1 + \lambda(q^2/m^2)$, where m is the pion mass and $q^2 = M^2 + m^2 - 2ME$ is the square of the four-vector momentum transfer, we obtain with 95% confidence the following limits on λ :

$$-0.05 \leq \lambda \leq 0.25.$$

From the analysis presented in this Letter we draw the following conclusions:

1. The data are consistent with the vector-coupling hypothesis. Within our statistical accuracy, the form factor f_V can be constant or have a variation within the limits quoted above for λ .
2. The data disagree with the tensor-coupling hypothesis for any choice of form factor.

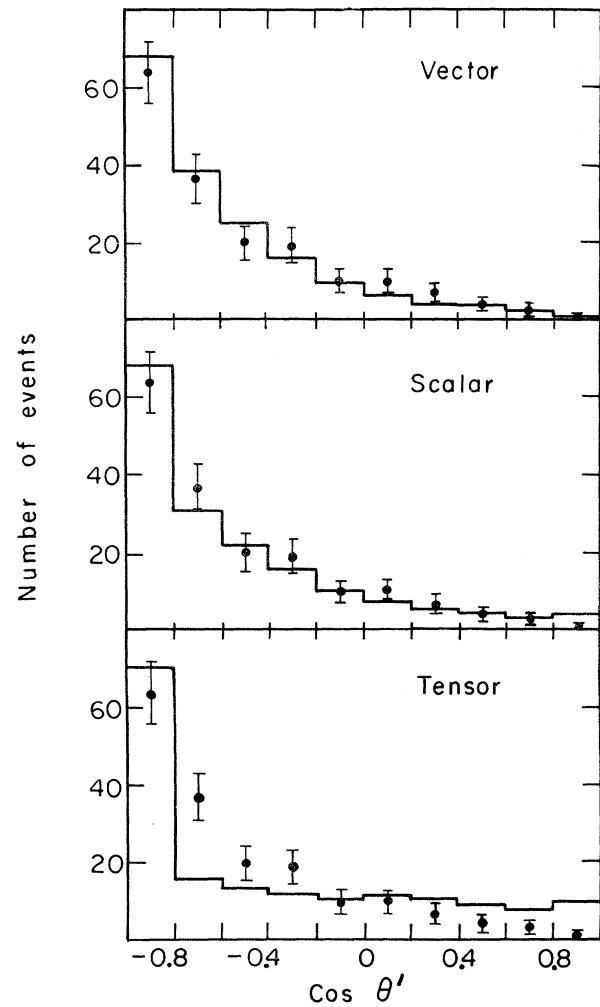


FIG. 2. Comparison between experimental and Monte Carlo $\cos\theta'$ distributions (θ' is the angle between the electron direction and the bisector of the angle ϕ). Varying form factors were chosen as described in text. The histogram represents the Monte Carlo results. The black circles with error flags represent our data.

3. If the scalar form factor is assumed to be slowly varying, the data disagree with the scalar hypothesis. However, we cannot rule out scalar coupling with a highly energy-dependent form factor that is very peaked at the upper end of the pion spectrum.

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¹This upper limit of 1% is derived in two ways: (a) In the emulsion data (see reference 5), roughly 20% of the K_{e3}^+ events have electron energies compatible, within measurement errors, with the value of 247 Mev expected for the K_{e2}^+ mode. Since the K_{e3} branching ratio is about 5%, the 1% limit follows. (b) In our own branching-ratio study (see reference 7), the observed small number of electron secondaries unaccompanied by electron pairs from π^0 gamma rays leads to an upper limit of less than 1% for the K_{e2} branching ratio.

²R. H. Dalitz, Rend. scuola. internaz. fis. "Enrico Fermi" **11**, 298 (1960).

³A. Pais and S. Treiman, Phys. Rev. **105**, 1616 (1957). In Eq. (1) we have considered only pure couplings.

⁴S. Furuichi, T. Kodama, S. Ogawa, Y. Sugahara, A. Wakasa, and M. Yonezawa, Progr. Theoret. Phys. (Kyoto) **17**, 89 (1957).

⁵M. Bruin, D. J. Holthuizen, and B. Jongejans, Nuovo cimento **9**, 422 (1958).

⁶D. Luers, I. S. Mitra, W. J. Willis, and S. S. Yamamoto, Phys. Rev. Letters **7**, 255 (1961).

⁷B. P. Roe, D. Sinclair, J. L. Brown, D. A. Glaser, J. A. Kadyk, and G. H. Trilling, Phys. Rev. Letters **7**, 346 (1961).

NEW RESONANCES AND STRONG INTERACTION SYMMETRY*

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Two of the most striking mysteries about the multitude of recently discovered resonances are the following:

(1) The branching ratio for Y_1^* ,

$$r = [Y_1^* \rightarrow (\pi + \Sigma)_{T=1}] / [Y_1^* \rightarrow \pi + \Lambda],$$

seems to be anomalously small, and is consistent with zero. The global symmetry model predicts $r = \frac{1}{2}(p_\Sigma/p_\Lambda)^3 = 11\%$ whereas the experimental ratio¹ is $4 \pm 4\%$.

(2) The width of the ω^0 meson ($\rightarrow \pi^+ + \pi^- + \pi^0$) is remarkably narrow and consistent with zero. The half-width at half maximum is reported to be less than 12 Mev.² (Recall that the total kinetic energy of the decay products is 370 Mev.)

These features once again suggest that there might be a symmetry higher than the symmetry implied by charge independence. We wish to point out that, in a class of theories which are sufficiently symmetric between N and Ξ , it is possible to forbid the $\pi\Sigma$ decay of Y_1^* and make the decay rate for $\omega^0 \rightarrow \pi^+ + \pi^- + \pi^0$ vanish to the extent that the $N\Xi$ mass difference could be ignored. Several other consequences of the postulated symmetry are discussed. We also show that the postulated symmetry is a natural consequence of the vector theory of strong interactions provided that N and Ξ (together with Λ and/or Σ) are treated as "fundamental" baryons (not as in the Sakata model).

Let us consider the following discrete operation

which we may call hypercharge reflection R .³

$$\begin{aligned} \begin{pmatrix} p \\ n \end{pmatrix} &\leftrightarrow \begin{pmatrix} \bar{p}^- \\ \bar{n}^0 \end{pmatrix}, & \begin{pmatrix} \Sigma^+ \\ \Sigma^0 \\ \Sigma^- \end{pmatrix} &\leftrightarrow \begin{pmatrix} \Sigma^- \\ \Sigma^0 \\ \Sigma^+ \end{pmatrix}, & \Lambda &\neq \Lambda, \\ \begin{pmatrix} \pi^+ \\ \pi^0 \\ \pi^- \end{pmatrix} &\leftrightarrow \begin{pmatrix} \pi^- \\ \pi^0 \\ \pi^+ \end{pmatrix}, & \begin{pmatrix} K^+ \\ K^0 \end{pmatrix} &\leftrightarrow \begin{pmatrix} K^- \\ \bar{K}^0 \end{pmatrix}. & & (1) \end{aligned}$$

The relative $N\Xi$ parity is assumed to be even, and the spin of the Ξ is assumed to be $\frac{1}{2}$; otherwise speculations given here would be useless. Suppose R is "good" to the extent that the $N\Xi$ mass difference could be ignored. We note that the $\pi \cdot (\vec{\Sigma} \times \Sigma)$ interaction, a typical term of which looks like $(\vec{\Sigma}^+ \Sigma^+ - \vec{\Sigma}^- \Sigma^-) \pi^0$, must vanish. In contrast the $\pi \cdot \vec{\Lambda} \vec{\Sigma}$ interaction is fully allowed. Now Y_1^* is known to decay into $\pi + \Lambda$; hence the phenomenological decay interaction $\pi \cdot \vec{\Lambda} \vec{Y}_1^*$ must be even under R . This immediately implies that Y_1^* must transform like $\underline{\Sigma}$, and that the phenomenological interaction $\pi \cdot (\vec{\Sigma} \times \vec{Y}_1^*)$ responsible for $Y_1^* \rightarrow \pi + \Sigma$ must vanish.

It also follows that R invariance forbids $\pi + \Lambda \neq \pi + \Sigma$, makes the one-pion exchange contribution to $N\Sigma$ forces vanish, and predicts the existence of a $T = \frac{3}{2}$, $p_{3/2}$ $\pi\Xi$ resonance analogous to the πN 3-3 resonance (as in the global symmetry model). The conjectured $\pi\Xi$ resonance may be looked for