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Authors

Brown, John L.
Kadyk, John A.
Trilling, George H.
et al.

Publication Date

1961-10-23

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

John L. Brown, John A. Kadyk, George H. Trilling, and Remy T. Van de Walle†

Lawrence Radiation Laboratory and Department of Physics
University of California, Berkeley
and
Byron P. Roe and Daniel Sinclair
Department of Physics, University of Michigan, Ann Arbor

October 23, 1961

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 Treiman 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:

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

for scalar coupling:

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

for tensor coupling:

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

Here 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, $K_2^0 \to e^\pm + \pi^\mp + \nu$ 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 point 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. 1a. The corresponding ϕ distributions, calculated with measurement errors of 2 deg folded in, are shown in Fig. 1b 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 conclusive 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 agree 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 Equation (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. 1a. 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. 1a. This procedure is justified by the excellent agreement between the experimental histogram and the vector curve in Fig. 1b. 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 betweeen 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.

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.

We wish to thank Professor D. A. Glaser for many helpful discussions connected with this experiment.

REFERENCES AND FOOTNOTES

* Work sponsored by U. S. Atomic Energy Commission.

† On leave from the Inter-University Institute for Nuclear Sciences, Brussels, Belgium.

1. This 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.
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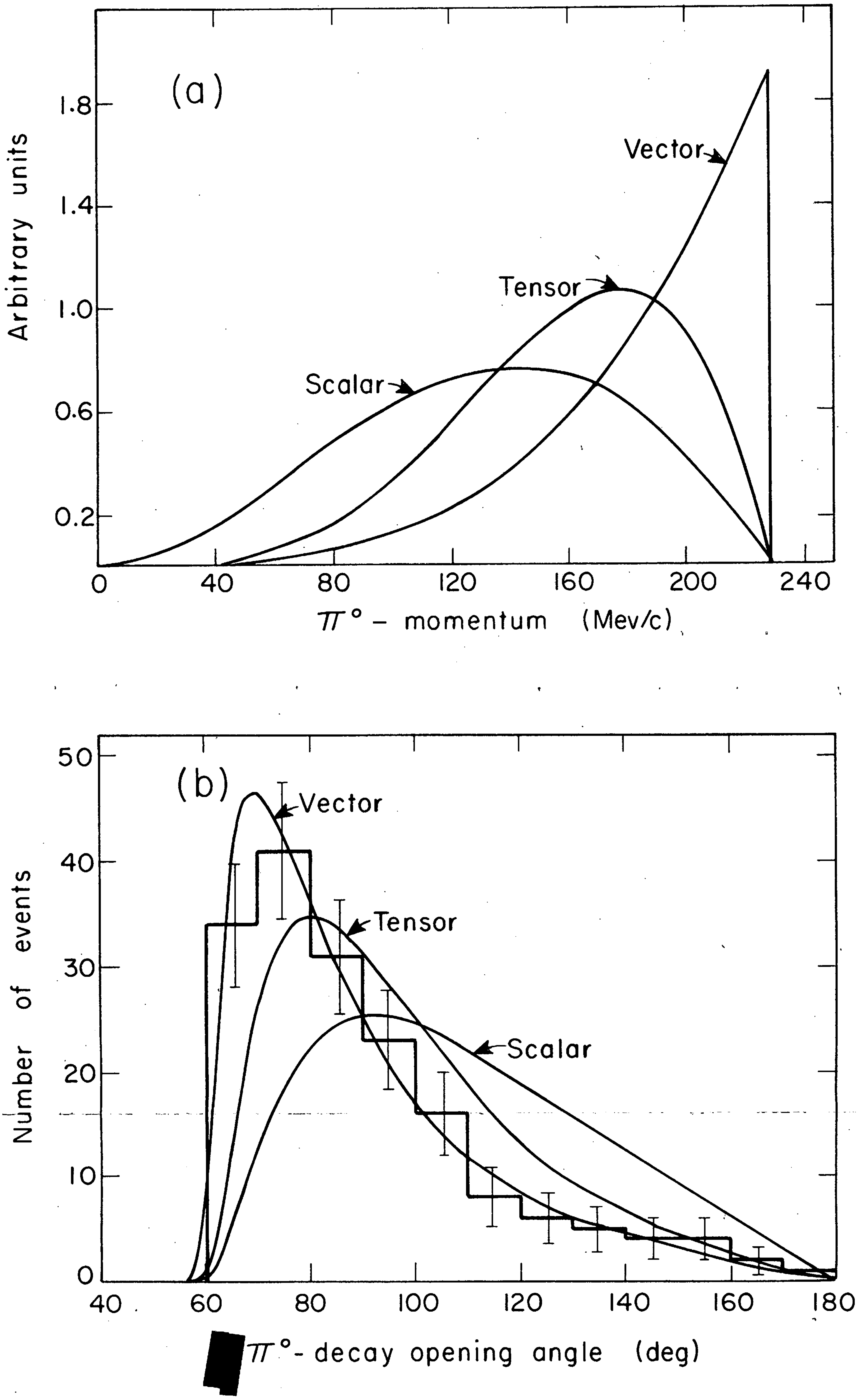
FIGURE LEGENDS

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.

Fig. 2. Comparison between experimental and Monte Carlo cos θ' 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.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160
200
240
π° - momentum (Mev/c)
(b)
Number of events
50
40
30
20
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Tensor
Scalar
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60
80
100
120
140
160
180
[redacted] π°- decay opening angle (deg)

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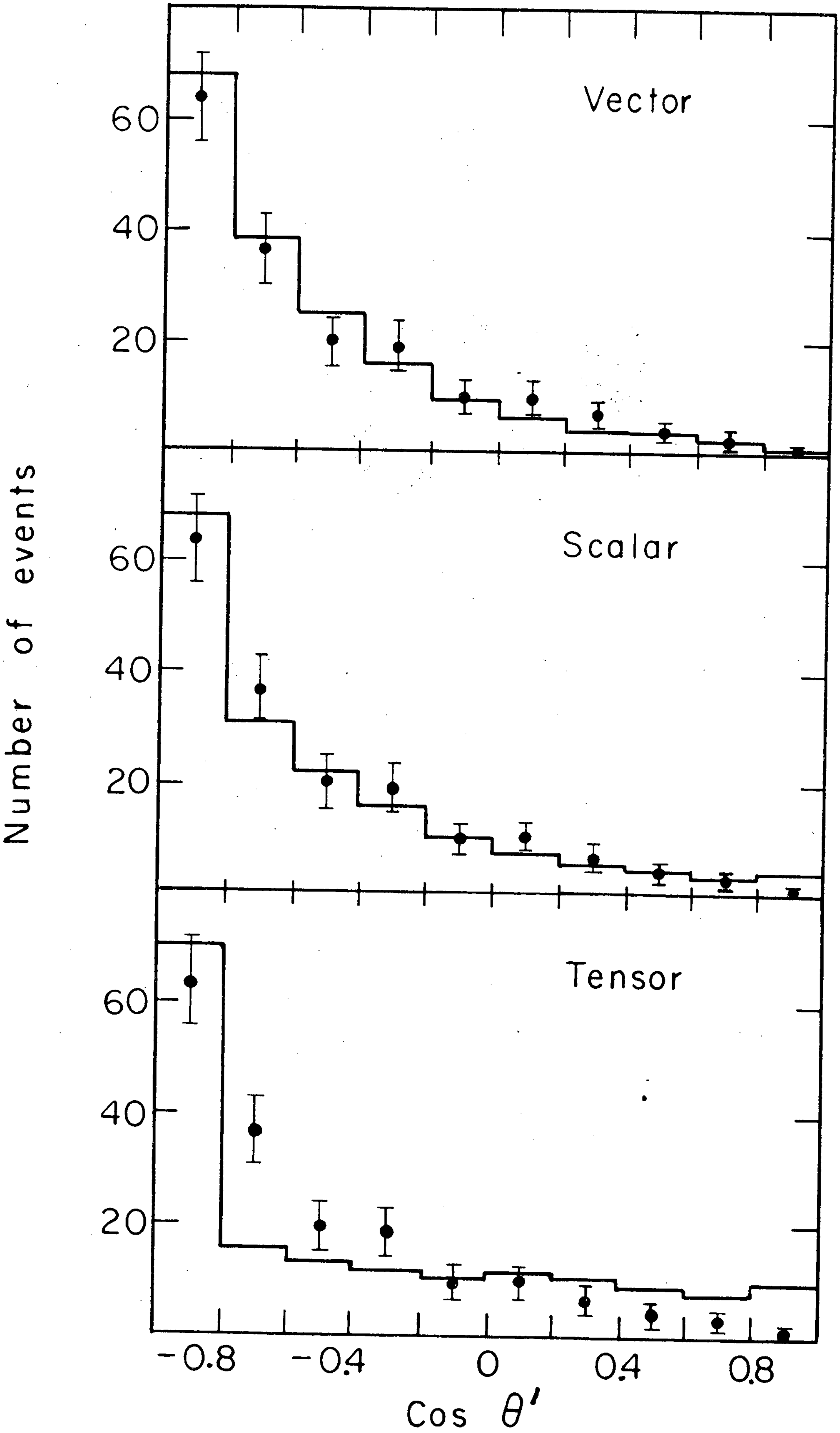
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Number of events
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-0.4
0
0.4
0.8
Cos θ′

Fig. 2

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