PHYSICAL REVIEW D

PARTICLES AND FIELDS

THIRD SERIES, VOL. 1, NO. 5 — 1 MARCH 1970

Upper Limit on the Structure-Dependent Radiation in $K^+ \to e^+ + \nu_e + \gamma$†

R. J. MACEK,* A. K. MANN, W. K. MCFARLANE,‡ AND J. B. ROBERTS§

Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

(Received 20 October 1969)

We have determined an upper limit to the branching ratio for the so-called structure-dependent radiation in the radiative decay mode $K^+ \to e^+ + \nu^e + \gamma$. The measurement was made by searching for moderate-energy photons in large-angle coincidence with positrons in the momentum region above the maximum allowed in K_{e3}^+ decay and below the momentum of K_{e2}^+. We obtain with 90% confidence $\Gamma_{e\nu\gamma}^{SD}/\Gamma(\text{all}) < 7.1\times10^{-5}$, assuming $\gamma_K \equiv A_K(0)/V_K(0) \geq 0$. This in turn yields $|V_K(0)| < 0.24 M_K^{-1}$, which is consistent with K^* dominance.

THE radiative decay mode $K^+ \to e^+ + \nu_e + \gamma$ is of interest because much of the radiation to which it gives rise probes the detailed structure of the states that couple the decaying kaon to the outgoing leptons. As a consequence, measurement of the form factors of this decay mode provides a useful test of the strong-interaction models invoked to describe the process. Furthermore, the coupling constants that make up the form factors are related by $SU(3)$ and current algebra to the coupling constants of other systems; hence tests of these $SU(3)$ relations and current-algebra sum rules become possible. Finally, a direct comparison may be made between this radiative decay mode and the corresponding decay mode $K^+ \to e^+ + \nu_e + \pi^0$.

The differential decay rate for the structure-dependent (SD) part of the process $K^+ \to e^+ + \nu_e + \gamma$ is given by[1]

$$\frac{d^2\Gamma^{SD}}{dxdy} = 3.47\times10^6 |V_K m_K|^2 [(1+\gamma_K)^2(x+y-1)^2(1-x) + (1-\gamma_K)^2(1-y)^2(1-x)], \quad (1)$$

where $x = 2E_\gamma/m_K$, $y = 2E_e/m_K$, and the electron mass has been set equal to zero; $\gamma_K = A_K/V_K$, and A_K and V_K are the SD radiative axial-vector and vector form factors, respectively. The q^2 dependence of the form factors has been neglected, and time-reversal invariance has been assumed. The terms in Eq. (1) multiplying $(1+\gamma_K)^2$ and $(1-\gamma_K)^2$ correspond to noninterfering final states with right- and left-helicity γ rays, respectively. From Eq. (1), $V-A$ helicity requirements on the leptons, and the conservation of linear and angular momenta, it follows that high-momentum positrons from this SD process are accompanied predominantly by right-helicity photons, and that these photons are emitted predominantly at large angles with respect to the positron momenta.

On the other hand, one has for the K_{e2} inner bremsstrahlung (IB)[2]

$$\frac{d\Gamma^{IB}}{dx\,d\cos\theta} = \frac{\alpha\Gamma_{e2}}{2\pi^2}\frac{1+\cos\theta}{1-\cos\theta}\frac{(x-1)^2+1}{[2+x(\cos\theta-1)]^2}\frac{1}{x}, \quad (2)$$

where $\alpha = 1/137$, Γ_{e2} is the rate of $K \to e\nu$, and θ is the angle between electron and photon directions. We see that in IB decays, low-energy photons (corresponding to high-energy electrons) are emitted almost exclusively at small θ. Thus searching for high-momentum positrons from K^+ decays in large-angle coincidence with γ rays should yield a clean sample of SD $K \to e\nu\gamma$ events, if the positron momentum is greater than the maximum allowable for K_{e3} decays.

The branching ratio for the analogous pion decay mode $\pi^+ \to e^+ + \nu_e + \gamma$ has been measured[3] to be $\pi \to e\nu\gamma$ (x and $y > 0.7$)$/\pi \to \mu\nu = (3.0\pm0.5)\times10^{-8}$. These authors assume the value of the vector form factor V_π obtained from conserved vector current, and use their measured branching ratio to obtain a value of $\gamma_\pi = A_\pi/V_\pi$. They find the quadratically ambiguous

† Work supported in part by the U. S. Atomic Energy Commission.

* Present address: Los Alamos Scientific Laboratory, Los Alamos, N. M.

‡ Present address: Temple University, Philadelphia, Pa.

§ National Science Foundation Predoctoral Fellow.

[1] Stanley G. Brown and Sidney A. Bludman, Phys. Rev. **136**, B1160 (1964).

[2] Sidney A. Bludman and James A. Young, Phys. Rev. **118**, 602 (1961).

[3] P. Depommier, J. Heintze, C. Rubbia, and V. Soergel, Phys. Letters **7**, 285 (1963).

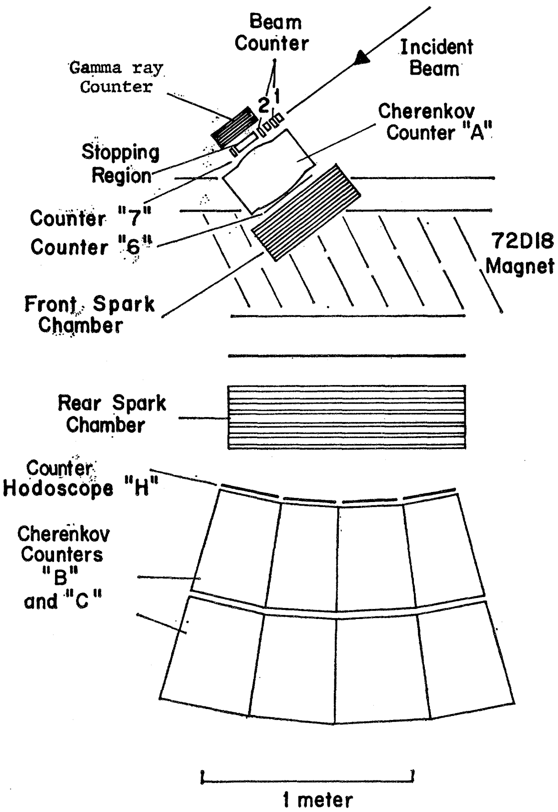


FIG. 1. Top view of the apparatus.

solutions $\gamma_\pi=+0.4$ and -2.1. The positive value of γ_π is in agreement with the calculated value assuming that the axial-vector structure of the decay is dominated by the A_1 meson.[4,5]

As a byproduct of a previously reported experiment[6] we have determined an upper limit to the branching ratio for the SD radiative decay $K^+\rightarrow e^++\nu_e+\gamma$. A diagram of the apparatus is shown in Fig. 1. Briefly, a coincidence of the three threshold gas Cherenkov counters A, B, and C assured the observation of a clean sample of electron events from the decays of stopped kaons. Selection of positrons from $K\rightarrow e\nu$ and high-positron-momentum $K\rightarrow e\nu\gamma$ events from the very abundant positrons emitted in K_{e3} decays was accomplished with the magnet-spark-chamber momentum spectrometer. The photons in large-angle coincidence with positrons were identified by the γ-ray counter, as indicated in Fig. 1.

In this experiment, no electron event arising from a K^+ decay whose momentum was greater than 234 MeV/c was observed in coincidence with a count from the γ-ray detector, as shown in Fig. 2(a). The finite resolution of the apparatus caused the $K_{e3}{}^+$ electron spectrum to spill out to 234 MeV/c from 228.5 MeV/c. This result was used to set an upper limit on the SD decay $K\rightarrow e\nu\gamma$. Normalizing by means of a known fraction of the $K_{e3}{}^+$ positron spectrum, we obtain with 90% confidence

$$\Gamma^{\rm SD}/\Gamma_{\rm all}<1.3\times10^{-5},\quad E_e>234\ {\rm MeV}/c,\qquad(3)$$

where $\Gamma_{\rm all}$ is the total K^+ decay rate.

As stated earlier, the percentage of high-momentum positrons in the Dalitz plot (accompanied by predominantly right-helicity photons) is determined by the $(1+\gamma_K)^2$ term in Eq. (1). Thus, the upper limit which the experiment can set on the total branching ratio for $K\rightarrow e\nu\gamma$ is dependent on the value of γ_K. Values of $|\gamma_K|$ have recently been calculated by two authors.[4,7] The results of the various methods vary from $|\gamma_K|=0.1$ to $|\gamma_K|=0.6$. Small values of $|\gamma_K|$ are likely because of the lack of any known intermediate state whose mass is lower than that of the K_A which can dominate the structure of the decay via axial-vector coupling. The mass of the K_A predicted by $SU(3)$ is 1310 MeV, compared to the known K^* mass of 885 MeV, which can dominate the structure by vector coupling. Also, as mentioned before, the positive solution of γ_π is in agreement with the theoretical prediction, and thus a positive value of γ_K is not unreasonable.

We obtain, with 90% confidence, for the total branching ratio for *any positive value* of γ_K,

$$\Gamma^{\rm SD}/\Gamma_{\rm all}<1.3\times10^{-4},\quad \gamma_K\geq0,\qquad(4)$$

if observation of an electron-γ-ray coincidence is required.

It is possible, however, to set a somewhat better upper limit on the rate $K\rightarrow e\nu\gamma$ if we require only the observation of positron events in the momentum region 234 to 247 MeV/c, without regard to coincidences with γ rays. There are contributions from K_{e2} and IB decays in this momentum region which must be subtracted from the observed number of positron events before an upper limit on $K^+\rightarrow e^++\nu_e+\gamma$ may be calculated. We estimate an expected number of 6.1 ± 0.65 positron events in this momentum region due to these sources, assuming $V-A$ theory with $\mu-e$ universality. (This number includes a small contribution from $K_{\mu2}$ and K_{e3} events.) There were five positrons actually observed in this momentum region. [See Figs. 2(a) and 2(b).] For all positive values of γ_K, we obtain with 90% confidence the improved limit on the total branching ratio

$$\Gamma_{\rm SD}{}^{K\rightarrow e\nu\gamma}/\Gamma_{\rm all}<7.1\times10^{-5},\quad \gamma_K\geq0.\qquad(5)$$

From this value we obtain an upper limit on the vector form factor

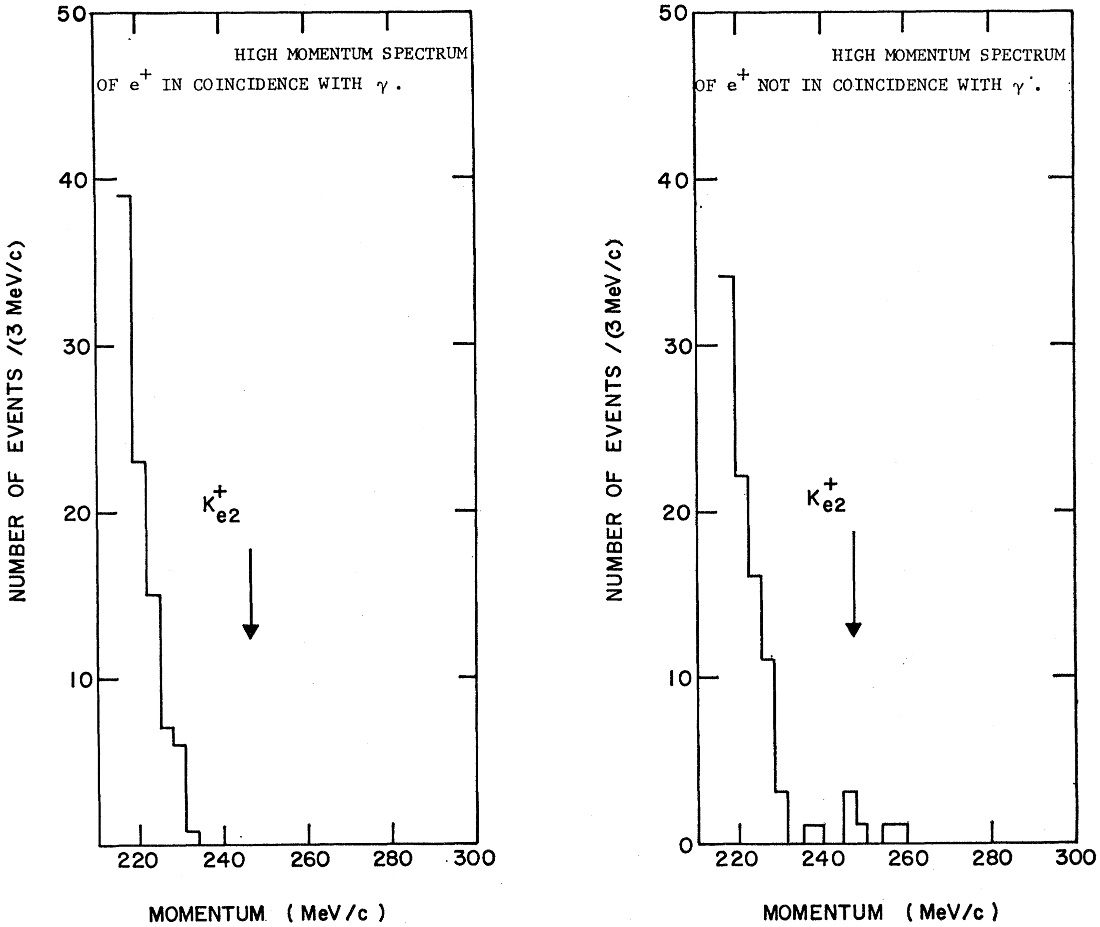
$$|V_K(0)|<0.24/M_K,\quad \gamma_K\geq0.\qquad(6)$$

[4] N. J. Carron and R. L. Schult, University of Illinois Report (unpublished).

[5] T. Das, V. S. Mathur, and S. Okubo, Phys. Rev. Letters **19**, 859 (1967).

[6] R. Macek, A. K. Mann, W. K. McFarlane, J. B. Roberts, K. W. Rothe, C. H. West, and L. B. Auerbach, Phys. Rev. Letters **22**, 32 (1969); J. B. Roberts, Ph.D. thesis, University of Pennsylvania, 1969 (unpublished).

[7] R. Rockmore, Phys. Rev. **177**, 2573 (1969).



(a) (b)

FIG. 2. (a) Spectrum of high-momentum positron events in coincidence with a γ ray. (b) Spectrum of high-momentum positron events not in coincidence with a γ ray.

If the structure of the decay via vector coupling is assumed to be dominated by the K^*, one has

$$V_K(0)=\frac{\sqrt{2}g_{K^*e\nu}G_{K^*K\gamma}}{M_{K^*}^2-M_K^2}, \qquad (7)$$

and thus in turn

$$|G_{K^*K\gamma}g_{K^*e\nu}|/M_K<0.38. \qquad (8)$$

This yields

$$|g_{K^*e\nu}|/M_{K^*}<1.6M_\pi=0.22 \text{ GeV}, \qquad (9)$$

if we assume the relation derived from $SU(3)$ symmetry,[4] $G_{K^*K\gamma}=\frac{1}{3}G_{\omega\pi\gamma}=0.98/\text{GeV}$, where $G_{\omega\pi\gamma}$ is obtained from the observed $\omega\rightarrow\pi+\gamma$ decay rate. Taking into account the effect of first-order symmetry breaking modifies this value only slightly.[8]

The upper limit of Eq. (9) may be compared to the combined prediction of the Kawarabayashi-Suzuki-Riazuddin-Fayyazuddin (KSRF)[9] relation and the Das-Mathur-Okubo[10] sum rule ($g_{K^*e\nu}^2/M_{K^*}^2=g_{\rho e\nu}^2/M_\rho^2=F_\pi^2$)

$$|g_{K^*e\nu}|/M_{K^*}=F_\pi=0.96M_\pi=0.134 \text{ GeV}, \qquad (10)$$

using the value of F_π from the experimental $\pi\rightarrow\mu\nu$ rate. A comparison may also be made with the result obtained by assuming K^* dominance in K_{e3}^+ decay, viz.,

$$|g_{K^*e\nu}|/M_{K^*}=0.138 \text{ GeV}. \qquad (11)$$

We may conclude that, if γ_K is positive, the coupling constants required in a calculation of the rate-determining form factor $V_K(0)$ based on K^* dominance are not significantly larger than those predicted by $SU(3)$ and appropriate current-algebra sum rules. In addition, V_K itself cannot be more than about a factor of 2 larger

[8] Neal Jay Carron, thesis, University of Illinois, 1969 (unpublished).

[9] K. Kawarabayashi and M. Suzuki, Phys. Rev. Letters **16**, 255 (1966); Riazuddin and Fayyazuddin, Phys. Rev. **147**, 1071 (1966).

[10] T. Das, V. S. Mathur, and S. Okubo, Phys. Rev. Letters **19**, 470 (1967).

than the value predicted by the K^* dominance model, which also accounts[4,8] for the magnitude of the vector form factor in K_{e3}^+.

We remark finally that a weakly interacting intermediate vector boson (W) may also mediate the decay $K\to e\nu\gamma$.[11,12] The form factor obtained using the W as an intermediate state is[12]

$$f(p^K\cdot p^\gamma) = \frac{(bg_W^2/M_W^2)[2-\mu_W-Q_W(p^\gamma\cdot p^K/2M_W^2)]}{M_W^2-M_K^2+2p^K\cdot p^\gamma}. \quad (12)$$

Reference 12 obtains the value of the coupling constant b from the experimental value of the kaon lifetime, and the value of g_W^2/M_W^2 from the β decay coupling constant. The branching ratio $\Gamma_{\mathrm{SD}}^{K\to e\nu\gamma}/\Gamma_{\mu2}$ is then calculated as a function of the W mass. The anomalous magnetic moment of W and its quadrupole moment are set equal to zero.

From the calculated branching ratio of Ref. 12 as a function of M_W, we obtain from the measured upper limit on the branching ratio the lower limit, $M_W>0.95$ GeV. This limit is somewhat lower than the limit, $M_W\gtrsim 2$ GeV, obtained by high-energy neutrino experiments.[13,14]

We would like to thank Dr. L. B. Auerbach, Dr. K. W. Rothe, and Dr. C. H. West for their efforts in the construction of the experimental apparatus and the analysis of the K_{e2} data, which was necessary for obtaining the $K\to e\nu\gamma$ results. D. Buchholz, H. Crothamel, and E. Mayer also contributed substantially to the design and construction of the apparatus. We wish to thank the staff of the Princeton-Pennsylvania Accelerator, where this experiment was performed, for their excellent cooperation.

[11] Donald E. Neville, Phys. Rev. **124**, 2037 (1961).
[12] S. M. Berman, A. Ghani, and R. A. Salmeron, Nuovo Cimento **25**, 685 (1962).
[13] G. Bernardini *et al.*, Nuovo Cimento **38**, 608 (1965).
[14] R. Burns *et al.*, Phys. Rev. Letters **15**, 42 (1965).

PHYSICAL REVIEW D VOLUME 1, NUMBER 5 1 MARCH 1970

Photoproduction of Electron Pairs as a Test of Quantum Electrodynamics

P. J. Biggs, D. W. Braben, R. W. Clifft, E. Gabathuler, P. Kitching, and R. E. Rand
Science Research Council, Daresbury Nuclear Physics Laboratory, Daresbury, Near Warrington, Lancashire, England
(Received 27 October 1969)

As a test of the validity of quantum electrodynamics (QED) for heavy virtual leptons, cross sections for wide-angle electron-pair photoproduction have been measured using hydrogen and carbon targets. Electron pairs were detected in two independent mirror-image spectrometers which identified production angles and momenta. A symmetrical arrangement was used in which interference between Bethe-Heitler and virtual Compton graphs is identically zero. Data were obtained at electron production angles from 5° to 7° and momenta from 1 to 2 GeV/c, and were compared with theory by means of a Monte Carlo calculation. Up to the maximum invariant mass of the electron pair 489 MeV/c^2, the data are consistent with the predictions of QED for both targets, confirming the results of other recent wide-angle pair-production and bremsstrahlung experiments in this energy range. Expressing the results in terms of a cutoff parameter Λ, where any positive deviation from QED is proportional to $\Lambda^{-4}Q_l^4$ (where Q_l is the mass of the virtual lepton), one obtains $\Lambda>0.76$ GeV/c^2 with 95% confidence. For a similar negative deviation, $\Lambda>0.55$ GeV/c^2.

1. INTRODUCTION

During the last few years a number of experiments have been performed to test the validity of quantum electrodynamics (QED). QED is, of course, the most complete of all available theories of elementary particle interactions and describes a wide range of phenomena with high accuracy. If it is pushed to extreme limits, however, in which the interaction takes place over a very short distance, it might be expected to break down. The forms of breakdown which may occur are modifications[1] of lepton or photon propagators when the particles are well off their mass shells, modification of the vertex function, and the introduction of heavy electromagnetic particles.[2]

These forms of modification are not strictly independent but any observed breakdowns could in practice be described in terms of one of them. The class of experiments with which we are concerned [wide-angle pair production (WAPP) and wide-angle bremsstrahlung (WAB)] is generally interpreted as testing the lepton propagator.

Much interest has been shown in this field since the original WAPP (electron) experiments at CEA[3] and Cornell[4] showed an apparently serious deviation from the predictions of QED. Subsequent similar experiments

[1] S. D. Drell, Ann. Phys. (N. Y.) **4**, 75 (1958).
[2] F. E. Low, Phys. Rev. Letters **14**, 238 (1965).
[3] R. B. Blumenthal, D. C. Ehn, W. L. Faissler, P. M. Joseph, L. J. Lanzerotti, F. M. Pipkin, and D. G. Stairs, Phys. Rev. **144**, 1199 (1966).
[4] R. M. Talman, Bull. Am. Phys. Soc. **11**, 380 (1966).