Search for Short-Lived Neutral Particles Emitted in K^+ Decay

N. J. Baker,[a] H. A. Gordon, D. M. Lazarus, V. A. Polychronakos, P. Rehak, and M. J. Tannenbaum
Brookhaven National Laboratory, Upton, New York 11973

J. Egger, W. D. Herold, and H. Kaspar
Swiss Institute for Nuclear Research, CH-5234 Villigen, Switzerland

V. Chaloupka, E. A. Jagel, and H. J. Lubatti
Department of Physics, University of Washington, Seattle, Washington 98195

and

C. Alliegro, C. Campagnari, P. S. Cooper, N. J. Hadley, A. M. Lee, and M. E. Zeller
Department of Physics, Yale University, New Haven, Connecticut 06511
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We have searched for the decay process $K^+ \to \pi^+ A^0$, where A^0 is any particle of mass less than 100 MeV/c^2 decaying into e^+e^-. Upper limits for the branching ratio are given as a function of mass and lifetime of the A^0. For lifetimes shorter than 10^{-13} sec, a limit of 4.5×10^{-7} at the 90% confidence level is obtained.

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The observation of correlated narrow electron-positron peaks in heavy-ion collisions[1] has sparked interest in the possible existence of a light (1.8 MeV/c^2), short-lived particle or resonance decaying into e^+e^-. One interesting possibility for such a particle is a short-lived axion which has been postulated by several authors as a solution to the problem of strong *CP* violation[2]; another is that of a light Higgs boson. We report here on a search for such particles, A^0, produced in the decay $K^+ \to \pi^+ A^0$, where A^0 decays into e^+e^- and has mass less than 100 MeV/c^2 and a lifetime shorter than 10^{-10} sec. Previous searches for this decay[3-6] were relatively insensitive to A^0 lifetimes less than 10^{-2} seconds or to masses less than the π^0 mass.[7]

The apparatus was located at the Brookhaven National Laboratory Alternating-Gradient Synchrotron in a 5.8-GeV/c positively charged, unseparated secondary beam. The number of K^+ per 1-sec spill varied from 2×10^6 to 5×10^6. The apparatus in plan view is shown in Fig. 1. Optimized for the decay $K^+ \to \pi^+\mu^+e^-$, it was designed to record kaons decaying into three charged particles and to provide efficient identification of electrons, pions, and muons. About 10% of the K^+ in the beam decayed in the evacuated decay volume 5 m upstream of the first spectrometer magnet, M1. This magnet was used to direct positive particles to the right side of the apparatus and negative particles to the left. The downstream magnet, M2, along with the four multiwire proportional chambers (MWPC's), P1–P4, provided momentum analysis. The MWPC's were deadened in the regions through which the beam passed. Each of the four MWPC's had three planes of wires, one mounted vertically and two others at $\pm18°$ to the vertical. The wire separation in all planes was 2 mm. The two threshold Cherenkov counters, C1 and C2, had 24 and 12 optical cells, respectively, and were split into two halves by a vertical opaque baffle along the center of the apparatus. The left-hand side of each counter, C1L and C2L, was filled with hydrogen, and the right-hand sides, C1R and C2R, with CO_2. Downstream of P4, there were two vertically oriented, 48-element trigger hodoscopes, S and F, followed by a lead scintillator calorimeter used to separate electrons from pions and muons. Further downstream was the muon detector, which consisted of eight alternating layers of proportional-tube chambers and 9-cm steel plates. Each proportional-tube chamber had one plane of horizontal and one plane of vertical wires.

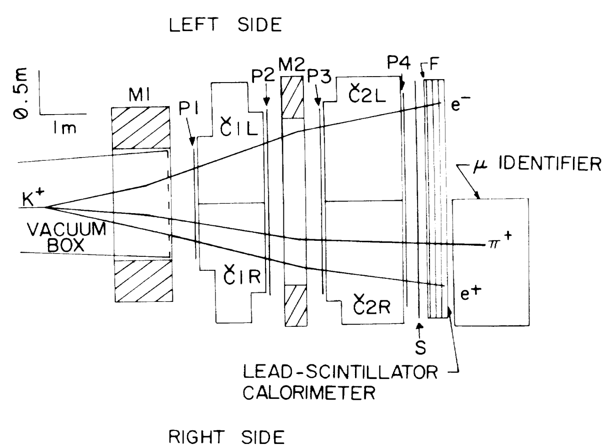

FIG. 1. Plan view of the apparatus.

The apparatus was triggered in up to three modes simultaneously. The first trigger mode required at least three scintillator hits in coincidence, a minimum of one on the left-hand side of the apparatus and two on the right-hand side. This trigger was sensitive to all K^+ decays into three charged tracks, the predominant mode being $K^+ \to \pi^+\pi^+\pi^-$, and was prescaled by a large factor, usually 8192, to reduce its high rate. The second trigger mode required additionally one electron (or positron) candidate on each side of the apparatus. It was satisfied by the decays $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-\gamma$ (Dalitz decay), $K^+ \to \pi^+e^+e^-$, and other decays with three charged particles including an e^+ and an e^-.

A total of 1.2×10^7 triggers was recorded. The data were processed by a chain of programs for pattern recognition and particle identification. The $K^+ \to \pi^+e^+e^-$ events were selected by use of geometrical and kinematical cuts obtained from the study of the numerous $K^+ \to \pi^+\pi^+\pi^-$ events, since both are three-track decays with no missing particles. The cuts were sufficiently loose to account for bremsstrahlung and to pass many Dalitz-decay events, where the γ is not measured, for normalization. The cuts were the following: (1) three tracks extrapolating to a vertex point, where the square root of the sum of the squares of the distances of closest approach of the tracks to the vertex, S, was less than 1.4 cm (S for K^+ decays has a mean value for 0.9 cm and a standard deviation of 0.5 cm as determined by Monte Carlo calculation); (2) vertex position and reconstructed kaon momentum consistent with the beam distributions as measured from the $K^+ \to \pi^+\pi^+\pi^-$ events; (3) the particle on the left side of the apparatus identified as an electron by C1, C2, and the calorimeter; (4) the two particles on the right side identified as a π^+ and a positron by C1, C2, and the calorimeter. The probability of a pion being identified as an electron or positron was less than 10^{-6} on the left side of the apparatus and less than 10^{-4} on the right side of the apparatus. The probability of a positron being identified as a pion on the right side of the apparatus was less than 10^{-3}. The pion was then required to be not consistent with a muon as seen in the muon identifier. The probability of a muon being identified as a pion was 10%. Approximately 2.8×10^4 events remained after these cuts.

From events satisfying the above criteria, we consider those with $\pi^+e^+e^-$ invariant mass ($M_{\pi ee}$) greater than 400 MeV/c^2 and less than 520 MeV/c^2, and with e^+e^- invariant mass (M_{ee}) less than 400 MeV/c^2. The data contain 11957 such events. For M_{ee} less than the π^0 mass, these events are consistent with Dalitz decays as generated by a detailed Monte Carlo simulation of the detector including the effects of finite resolution, multiple scattering, and electron bremsstrahlung. The contribution from other K^+ decays, considering relative acceptances and particle misidentification probabilities, is less than 0.2%. The background in this sample from sources other than K^+ decays, as estimated by the study of $K^+ \to \pi^+\pi^+\pi^-$ decays, is less than 2%.

In order to remove events with unmeasured particles and missing neutrals, we next required that the reconstructed kaon-momentum vector extrapolate back to the production target located 5 m upstream of the entrance to the decay region. After this requirement, 3427 events remain in the $M_{\pi ee}$ and M_{ee} mass regions shown in Fig. 2(a). We now examine three regions of the plot in detail. Figure 2(b) displays the distribution of $M_{\pi ee}$ for $M_{ee} \geq 150$ MeV/c^2, and shows a signal of nine events at the K_+ mass. This signal is consistent with the direct decay $K^+ \to \pi^+e^+e^-$ for which the branching ratio is $(2.7\pm0.5)\times10^{-7}$.[5] By cutting at $M_{ee} \geq 150$ MeV/c^2, we avoid contamination from π^0 decays. In Fig. 2(c), we show the distribution of $M_{\pi ee}$ for $M_{ee} \leq 15$ MeV/c^2. This would be the signal region for a 1.8-MeV/c^2 A^0 whose natural width is less than our resolution. Events from $K^+ \to \pi^+A^0$ would have an rms width of 10 MeV/c^2 and, as a result of radiative effects, would be centered 1 MeV/c^2 below the K^+ mass (M_K). In the region of M_K, there are events from Dalitz decay on the low-mass side and a single event on the high-mass side. To minimize the Dalitz-decay background, we consider events where 492.5 MeV/$c^2 \leq M_{\pi ee} \leq 520.0$ MeV/c^2, and, to evaluate potential signals, consider the M_{ee} distribution up to 100 MeV/c^2.[8] The plot of M_{ee} for this $M_{\pi ee}$ range is shown in Fig. 2(d), along with the expected signal from the decay of a 1.8-MeV/c^2 A^0. The apparatus acceptance peaks at large M_{ee}, and we estimate there to be less than one event from direct $K^+ \to \pi^+e^+e^-$ decays in this M_{ee} region. There are no significant concentrations of events in the plot, and the distribution of events is consistent with our Monte Carlo simulation of Dalitz decays. Treating the events in Fig. 2(d) as constant background, we calculate an expected background of 1.4 events in the region $M_{ee} \leq 15$ MeV/c^2.

We can then determine an upper limit for the process $K^+ \to \pi^+A^0$ where A^0 decays into e^+e^-. We normalize to Dalitz decays, since they have the same observed particles in the final state, using the formula

$$B(A^0) = \frac{N(A^0)}{N(\text{Dalitz})}\frac{G(\text{Dalitz})}{G(A^0)}B(\text{Dalitz}).$$

$B(A^0)$ is the branching ratio for $K^+ \to \pi^+A^0$, $A^0 \to e^+e^-$. B(Dalitz) is the product of the branching ratios for $K^+ \to \pi^+\pi^0$, $\pi^0 \to e^+e^-\gamma$; $B(\text{Dalitz}) = 2.54\times10^{-3}$. $N(A^0)$ is the upper limit on the number of $K^+ \to \pi^+A^0$ events; $N(A^0) = 3.1$.[9] N(Dalitz) is the number of Dalitz events with $M_{ee} \leq 100$ MeV/c^2 and 400 MeV/$c^2 \leq M_{\pi ee} \leq 470$ MeV/c^2; $N(\text{Dalitz}) = 11084$. G(Dalitz) is the acceptance for Dalitz events including all kinematic cuts, except that requiring extrapolation to the target; $G(\text{Dalitz}) = 2.0\times10^{-3}$. $G(A^0)$ is the acceptance for $K^+ \to \pi^+A^0$, $A^0 \to e^+e^-$, including all the above cuts. $G(A^0)$ depends on the A^0 lifetime and mass, and is 3.2×10^{-3} for a lifetime less than 10^{-13} sec and a

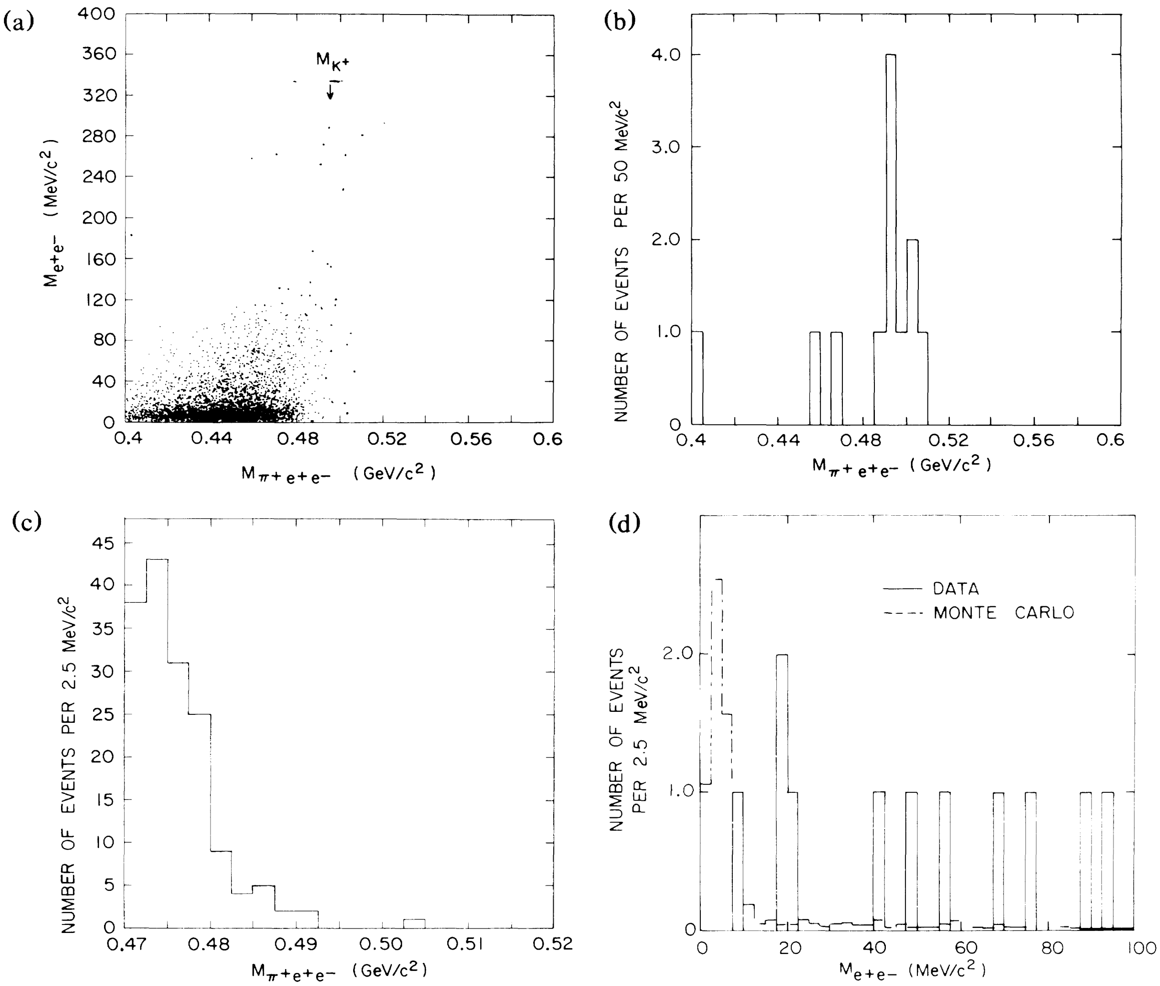

FIG. 2. (a) Scatter plot of M_{ee} vs $M_{\pi ee}$ with the requirement that the reconstructed K^+ momentum vector point back to the production target. The arrow is drawn at the K^+ mass. (b) Distribution of invariant mass $M_{\pi ee}$ for $M_{ee} \geq 150$ MeV/c^2. (c) Distribution of $M_{\pi ee}$ for $M_{ee} \leq 15$ MeV/c^2. (d) Distribution of M_{ee} for 492.5 MeV/$c^2 \leq M_{ee} \leq 520$ MeV/c^2. The dashed line indicates the signal expected from the decay of a 1.8-MeV/$c^2 A^0$ with $B(A^0)$ equal to 10^{-6}. The high-mass tail on this Monte Carlo distribution is the result of electron bremsstrahlung and multiple Coulomb scattering.

mass of 1.8 MeV/c^2. The uncertainty on the ratio of acceptances G(Dalitz)/$G(A^0)$ is less than 10%. For an A^0 with the above mass and lifetime, we obtain the limit $B(A^0) \leq 4.5 \times 10^{-7}$ at the 90% confidence level.

A plot of $B(A^0)$ limit versus lifetime for an A^0 with mass 1.8 MeV/c^2 is given in Fig. 3 along with limits from Ref. 7 based on the data from Refs. 3 and 4. From this figure, one sees that our branching-ratio limit complements that of previous searches and significantly reduces the possibility of A^0 production through this K^+ decay channel. Taken with the published limits for $\pi^+ \to A^0 e^+ \nu$,[10] these results confirm the rejection of axion-model variants which were inspired by the observations in heavy-ion collisions.[11]

Also shown in Fig. 3 is the $B(A^0)$ limit versus lifetime for an A^0 with mass 100 MeV/c^2. For masses greater than 10 MeV/c^2, our e^+e^- mass resolution was calculated to be 4 MeV/c^2 (rms) and we use a ± 10-MeV/c^2 region about the A^0 mass as the signal region. For lifetimes such that the A^0 travels much less than 1.4 cm in the lab before decaying, our limit for $B(A^0)$ is less than 8×10^{-7} at the 90% confidence level for all values of the A^0 mass. This latter result severely constrains the possibility of the production of more massive e^+e^- states in $K^+ \to \pi^+ A^0$. Our result is below the branching ratio of 10^{-4} calculated for a light Higgs boson by Willey and Yu[12] and by Vainstein, Zakharov, and Shifman,[12] although it is larger than the prediction of 10^{-8} by Pham and Sutherland.[13]

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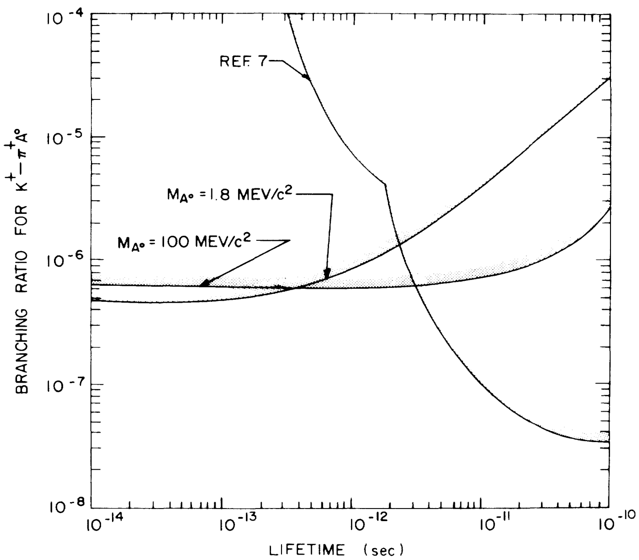

FIG. 3. $B(A^0)$ for A^0 mass equal to 1.8 MeV/c^2 and 100 MeV/c^2 (this experiment), and for A^0 mass equal to 1.8 MeV/c^2 from Ref. 7 for data from Refs. 3 and 4. Areas above the respective lines are excluded with greater than a 90% confidence level.

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[(a)]Present address: Bear, Stearns, & Co., New York, NY.

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