We find no significant difference in the measured cross-section results by using the center counter alone rather than the sum of all three. Therefore, the measured cross sections are not significantly dependent upon the experimental resolution. The resolution in photon energy for all three counters is typically 18 MeV at 222 and 254 MeV, 20 MeV at 302 MeV, and 25 MeV at 342 MeV except for proton c.m.-system angles larger than 130° where the resolution becomes larger because of the increased energy loss in the target. The most striking features of the data are the well-known peak in the total cross section at about 260 MeV and the rapid falloff with increasing photon energy. The peak is due to the virtual excitation of the 1236-MeV N^* resonance. The differential cross-section data extend to more forward and backward angles than previous experiments and show a tendency towards leveling off towards forwards and backwards angles. This is particularly observed in the 302- and 342-MeV data.

The most recent and complete calculation of the photodisintegration is the one of Hasselmann.[10] In contrast to earlier calculations, it is in reasonable agreement with the experimental data for the differential cross section.

A more detailed account of the experiment and comparison with theory will be published elsewhere.

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TEST OF THE $\Delta S=\Delta Q$ RULE IN $K^0 \to \pi e \nu$ DECAY*†

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K^0's were produced by the charge exchange of K^+'s in Cu targets and the subsequent decays observed in a spark chamber situated in a magnetic field. The time distribution of 686 selected events yields $\mathrm{Re}x = 0.09 \pm 0.15$, $\mathrm{Im}x = -0.11 \pm 0.11$ if x is allowed to be complex, and $x = 0 \pm 0.12$ if x is constrained to be real. Thus, while several previous chamber results seemed to converge on $x \simeq 0.2$ as the most probable value, our data shift somewhat the likelihood distribution in favor of the $\Delta S=\Delta Q$ rule.

An important and attractive simplification in the description of weak-interaction phenomena is obtained if one postulates the rule $\Delta S = \Delta Q$ for all decays for which $\Delta S = \pm 1$.[1] The so-called $K_{e3}{}^0$ decay ($K^0 \to \pi e \nu$) is a convenient reaction for such a test, and several experiments[2] have been reported which studied this decay.

We report here a new experiment on $K_{e3}{}^0$ decay which used a spark chamber in a magnetic field followed by a lead chamber for the recognition of electronic events. The analysis is based on a final selection of 686 events.

Experimental apparatus.– Figure 1(a) shows the experimental apparatus which utilized a 990-MeV separated K^+ beam,[3] produced by the Lawrence Radiation Laboratory Bevatron. The intensity of

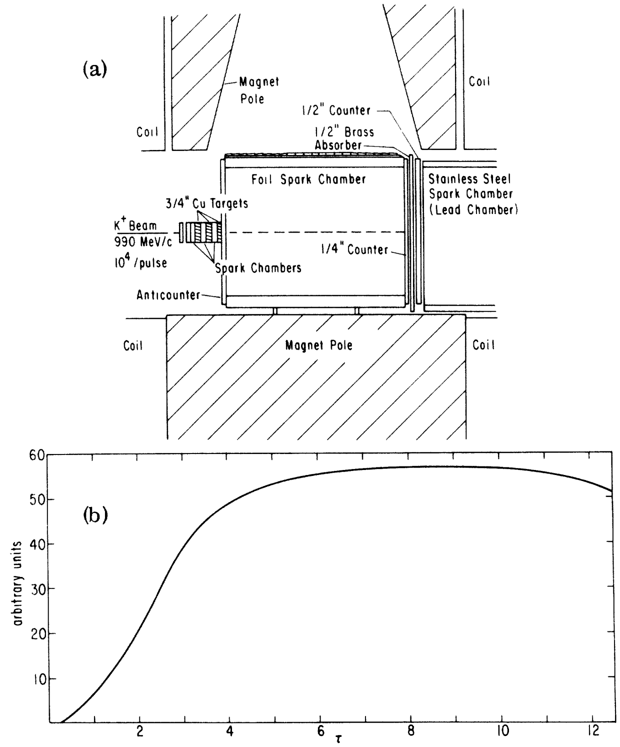

FIG. 1. (a) Experimental apparatus. (b) Detection efficiency.

the beam was 10^4 K^+/pulse, and the background ratio (essentially all π's) was 1:1. (This residual background was electronically eliminated by a Cherenkov counter.)

The K^+ particles passed through an array of three small spark chambers (A chamber) and three 2-cm Cu targets. The small spark chambers allowed the determination of the charge-exchange point. About eight out of 10^4 K^+ produced a K^0 in the useful solid angle. The K^0's passed through a large scintillator in anticoincidence to eliminate triggering by charged particles. Next, there was a large thin-foil spark chamber[3] (B chamber, $60.3\times 44.5\times 72.3$ cm^3) which had 46 $\frac{1}{2}$-in. gaps. This was followed by two scintillation counters separated by a $\frac{1}{2}$-in. brass absorber.

After the B chamber, there was an array of 12 ($\frac{1}{2}$-in. gap) stainless-steel spark-chamber modules, separated by $\frac{1}{8}$-in. lead plates, to detect the electron showers. This array we refer to as the "lead chamber."

The B chamber was placed in a 10-kG magnetic field so that the sign and momentum of the charged secondaries could be measured with an error of 4% for the long track of a typical decay event and 20% for the short track.

Two cameras were set up for 90° stereo of the A and B chambers and a partial stereo view of the lead chamber. An average of three pictures were taken per Bevatron pulse for a total of 1.3×10^6 events.

Scanning and selection of pictures. — All the pictures were scanned once and 15 % were scanned twice for "V's," one of whose tracks seemed to produce an electron shower in the lead chamber. Criteria for what constituted such a shower were decided on by analyzing pictures taken with a pure pion and a pure electron beam separately.

In short, the elements on which the criteria were based were the number M_S of sparks out of line, and the number M_g of spark-chamber gaps which did not fire in spite of being in the path of a track. It was required that the sum M_S+M_g be at least 2. The number of sparks aligned as if produced by a meson or other heavy particle was a criterion used to exclude the event.

About 40 000 events were selected. The pictures were then optically copied onto new 35mm film so that the new rolls contained only candidates for measurement. The total number of measured events passing the fitting program KADAP[3] was 32 815. In addition, several rolls of original film had every "V" measured, regardless of the lead chamber, for a total of 12 500 events which were used for determining background.

The 32 815 pictures were then subjected to kinematical criteria based on how far the event was from fitting a K_S decay and to more strict visual criteria applied by physicists. Each selected picture was independently analyzed by two persons.

For the proper-time interval 0 to $9.5t_S$ ($t_S=K_S$ mean life), the appearance of the electron shower was expressed as a grade (A, B, C), and progressively more severe kinematic criteria (see next section) were applied to A, B, and C events.

To test the efficiency of the visual criteria, pictures have been taken with pure pion and electron beams; also, we had enough pictures of pure K_S and pure γ-pair events so that we could obtain separately the efficiencies for accepting an electron, E_A, E_B, E_C, and the probabilities of erroneously accepting a pion or a proton, P_A, P_B, P_C.[4]

Residual background. — The difficulty of an experiment such as the present one is due to the fact that only one in 500 of the "V" events observed in the most important time interval is a $K_{e3}{}^0$ decay which we want to study. To compute how many wrong events filter through our criteria, we did the following. For 12 500 pictures, we measured all "V's" and we applied the kinematic criteria K_A, K_B, K_C proper for the respective grades A, B, and C. (See previous section.) N_A', N_B', N_C' events survived, respectively, from which numbers we concluded, by a simple proportion, that, had we measured all the "V's" in the whole film, N_A, N_B, N_C events would have survived the kinematic criteria. On the other hand, the final selected events numbered M_A, M_B, M_C. Knowing the efficiencies E_A, E_B, E_C, we then computed that N_A contains M_A/E_A good events, and so on. Since we know that the $(N_A - M_A/E_A)$ wrong events have a probability P_A of filtering through, we conclude that the residual background is equal to $(N_A - M_A/E_A)P_A$. This computation was done separately for each interval of T.

A small correction had to be applied because the $K_{\mu 3}$ events (contained among the wrong events actually had probability even less than P to be accepted. Beside this direct way of computing the background, a further check of its value was obtained from the K_S peak in the 2π-mass equivalent spectrum for all "V's." Without going into details, we want to mention that, on this basis, it was possible to compute also the K_S acceptance probability P_K using kinematic criteria only which has not entered explicitly in the above treatment.[5]

A special consideration was also given to Dalitz-pair contamination. We excluded from the selected events those for which $M(e^+,e^-)$ was <80 MeV. We also plotted $M(e^+,e^-)$ for all events selected by the first scan and looked for an enhancement at low values. From this we estimated that the entire film contained 445 Dalitz pairs and, out of those, only 2.4 survived the final condition $M(e^+,e^-)<80$ MeV.

The contamination from 3π decays was also cross checked by plotting the 3π discriminant.[6]

Analysis.—Assuming CPT invariance, the amplitudes for the various final states of the $K_{e3}{}^0$ decays are as follows: For $\Delta S = \Delta Q$,

$$\mathrm{Amp}(K^0 \to e^+\pi^-\nu) = f,$$

$$\mathrm{Amp}(\bar{K}^0 \to e^-\pi^+\bar{\nu}) = f^*;$$

for $\Delta S = -\Delta Q$,

$$\mathrm{Amp}(K^0 \to e^-\pi^+\bar{\nu}) = g^*,$$

$$\mathrm{Amp}(\bar{K}^0 \to e^+\pi^-\nu) = g. \qquad (1)$$

In addition, CP conservation requires f and g to be real. Therefore, a suitable measure of both $\Delta S = \Delta Q$ and CP nonconservation is the parameter $x = g/f$.[7] (If $x \neq 0$, then $\Delta S = \Delta Q$ is violated and if x has an imaginary part, CP is violated.)

x can be determined from the time distribution of $K_{e3}{}^0$ decays. If (as in our experiment) one starts from a beam of pure K^0's, the time distribution of the decays into positrons or electrons in the system of reference of the K^0 is[8]

$$N^{\pm}(t) = \tfrac{1}{4}|f|^2[|1+x|^2 e^{-\lambda_S t} + |1-x|^2 e^{-\lambda_L t} + 4\,\mathrm{Im}x \sin(\delta t) e^{-\bar{\lambda} t} \pm 2(1-|x|^2)\cos(\delta t) e^{-\bar{\lambda} t}]. \qquad (2)$$

As in most experiments, our efficiency for detecting and identifying an event is not constant for all values of the proper time t and it can be computed only approximately. Our Monte Carlo-computed curve is shown in Fig. 1(b). On the other hand, the ratio N^-/N^+, as a function of t, which is independent of the detection efficiency, is a very reliable quantity because our apparatus had essentially no bias toward either sign and the magnetic field was alternated several times. Therefore, the sum $N^+ + N^-$ and the ratio were fit separately [see Figs. 3(a) and 3(b)]. The results were consistent [Figs. 3(c) and 3(d)].

The proper time t, which appears in (2), is computed from the position of the vertex, the position of the charge-exchange point, and the measured momenta of the two tracks, p_1 and p_2. (We designate as 1 the track which triggers the apparatus and enters the lead chamber.)

It is well known that the momentum of the K^0, p^0, is in such a case determined only with a quadratic ambiguity, $p^0 = a \pm \sqrt{\Delta}$. Because the p^0 spectrum [Fig. 2(b)] is only 300 MeV/c in width, 29% of the events actually had no such ambiguity, while for another 24% Δ was practically zero. For the irreducibly ambiguous events, we took the most probable solution and computed, fairly accurately, the "smearing" caused by the double choice.

This computation was made using a fairly sophisticated Monte Carlo program which, given an

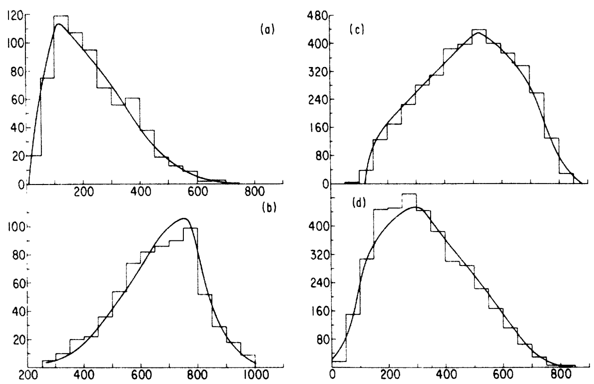

FIG. 2. Comparison between Monte Carlo computation and observed spectra of (a) momentum (p_2) of the second track for K^0-$e3$ events, (b) K^0 momentum P_{K^0} for the same K^0-$e3$ events, (c) momentum (p_1) of the first (triggering) track and (d) of second track for recognized K_S events.

input K^0 spectrum, could compute a sample of K_S, $K_{e3}{}^0$, and $K_{\mu 3}$ decays likely to be observed in our pictures, giving the momentum values expected to be obtained from measurements and taking into account experimental errors.

The K^0 momentum spectrum[9] for the Monte Carlo program cannot be correctly computed from known cross sections because it depends upon the details of the apparatus such as the thickness of the target and its distance from the anticoincidence counter. However, the analysis of the recognized K_S events allowed us to compute the effective K^0 spectrum at production.

Figure 2 shows the degree of agreement between the Monte Carlo–computed histograms and the observed ones. It is worth noting that, since the input spectrum was not adjusted in order to obtain a better fit for the $K_{e3}{}^0$ quantities, nor for the other two curves of Fig. 2, the matching of the four curves with the corresponding histograms is a nontrivial comparison.

Conclusion. —The fit of our results to the different x values is shown in Fig. 3. If both CP invariance as well as the $\Delta S = \Delta Q$ rule are to be questioned in $K_{e3}{}^0$ decay, that is if we allow x to have an imaginary part as well as a real part, then we must rely heavily on the computed efficiency versus t because the N^-/N^+ ratio [Fig. 3(c)] allows too large an interval of values for

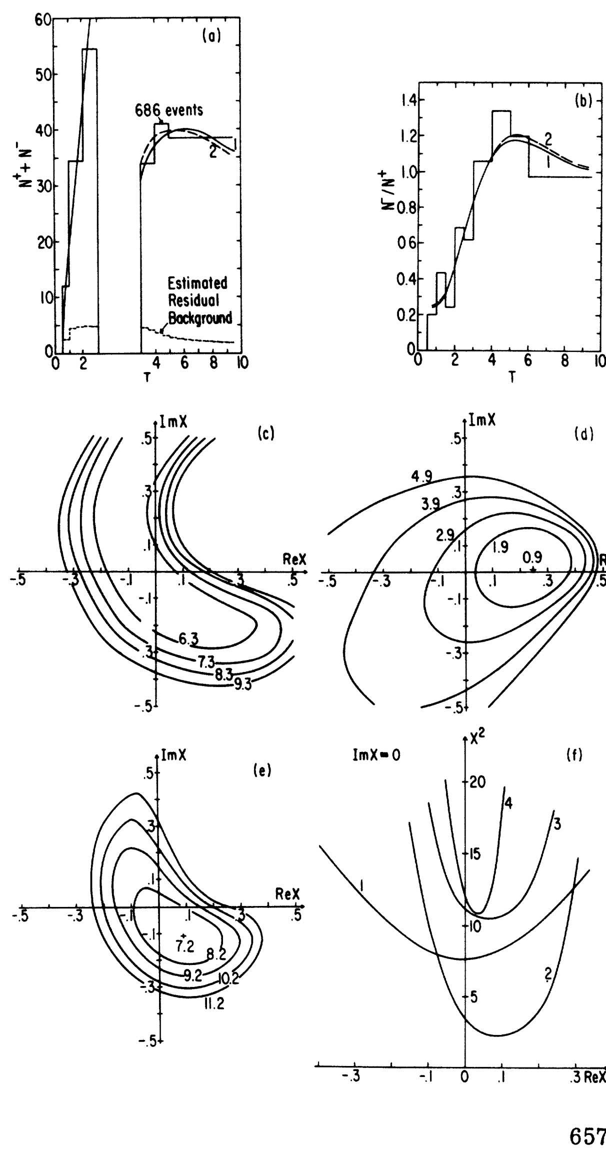

FIG. 3. (a) Time distribution of $N^+ + N^-$ (solid histogram). Curves 1 and 2 are the Monte Carlo–computed distribution for $x = 0$ and for $x = 0.09 - 0.11i$ (best fit). The estimated residual background is also shown. Note: The separation in two intervals reflects the fact that the efficiency for electron recognition might not be the same because the scanning for the two regions was done in slightly different ways. (b) Time distribution of N^-/N^+. Curves 1 and 2 have the same meaning as explained above. The consideration of the Note in (a) has, of course, no bearing in the ratio N^-/N^+. (c) χ^2 contours for the ratio $R = N^-/N^+$. Curves for χ^2 increments of 1 are shown. R is independent of the efficiency for recognizing electrons and largely independent of the parameters used in the Monte Carlo computation. $\chi_{min}{}^2 = 5.3$ for seven degrees of freedom. (d) χ^2 for $S = N^- + N^+$. $\chi_{min}{}^2 = 0.9$ for three degrees of freedom. (e) χ^2 for simultaneous fitting of R and S. $\chi_{min}{}^2 = 7.2$ for 12 degrees of freedom. (f) χ^2 versus real x, where the condition $\mathrm{Im}x = 0$ is applied. Curve 1: present experiment, $x = 0 \pm 0.12$; curve 2: previous visual chamber experiments, $x = 0.087_{-0.077}^{+0.088}$; curve 3: the sum of curves 1 and 2: $x = 0.065 \pm 0.07$; and curve 4: the sum of curves 1 and 2 and counter data of Ref. 10, $x = 0.037_{-0.033}^{+0.025}$.

Imx. Our result [Fig. 3(e)] is Re$x = 0.009^{+0.14}_{-0.16}$, Im$x = -0.11^{+0.10}_{-0.11}$.

However, in view of the fact that, of all particle reactions studied in the last four years, still the only example of CP nonconservation is the $K_L \to 2\pi$ decay, and since it seems, more and more, that this nonconservation is confined to the fact that the compositions K_L, K_S are not CP eigenstates rather than to CP nonconservation in the decay interaction, it is perhaps more interesting to look at the result under the condition Im$x = 0$. That we have done in Fig. 3(f). We see then that our experiment gives $x = 0 \pm 0.12$ and, combining it with all previous chamber experiments, we obtain $x = 0.065 \pm 0.07$. With the addition of the recent, high-statistics, counter experiment of Bennett et al.,[10] we have $x = 0.037 \pm ^{0.025}_{0.033}$. Thus, it appears that, unless CP is not conserved in $K_{e3}{}^0$ decay, the $\Delta S = \Delta Q$ amplitude is at least ten times the $\Delta S = -\Delta Q$ one.

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