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Self-Contained Determination of the Phase of η_{+-}*

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In a single K^0 regeneration experiment, all the parameters needed to specify the phase of the CP-noninvariant parameter η_{+-} have been measured concurrently. The $K_{\pi 2}$ data have given the η_{+-} phase relative to the phase of the K_1^0 regeneration, while the regeneration phase has been measured directly using the K_{e3} charge asymmetry. Incorporated in the latter measurement is an experimentally determined correction for the effects of incoherent regeneration. The experiment yields $\arg\eta_{+-} = 36.2° \pm 6.1°$.

I. INTRODUCTION

The coherent production of K_1^0 mesons from long-lived K_2^0 mesons passing through material has provided an extraordinarily valuable tool for studying not only the K_1^0-K_2^0 system in detail but also the parameters which characterize the CP noninvariance observed in K_2^0 decay to two pions. The interference between the amplitude for 2π decay which results from the coherent scattering of K_2^0's in material (coherent regeneration) and the amplitude for direct decay $K_2^0 \to 2\pi$ has been an important source of information on the phase of η_{+-}, the ratio of the amplitudes for $K_2^0 \to \pi^+\pi^-$ and $K_1^0 \to \pi^+\pi^-$. Specifically, the interference pattern in the 2π rate observed downstream from a regenerator is characterized by a phase term $\cos(\varphi_{+-} - \varphi_\rho + \delta\tau)$, where φ_{+-} is the argument of η_{+-}, φ_ρ is the phase (relative to the K_2^0 wave) with which the K_1^0 wave has been coherently produced in the material, τ is the proper-time interval between exit from the material and decay (in units of the K_1^0 lifetime, τ_1), and δ is the K_1^0-K_2^0 mass difference in units of $1/\tau_1$. Therefore, with δ known,[1-3] the study of the interference leads to knowledge of $\arg\eta_{+-}$ only after independent information on the phase of the coherent regeneration has been obtained. This phase depends on K^0 and $\bar{K}^0$ nuclear scattering amplitudes about which there is no direct information. The usual approach[4] to getting this input has been to use whatever K^+ and K^- nucleon scattering information is available, assume charge symmetry and the validity of the optical model, and compute the regeneration phase. Alternatively, total cross section data for K^+ and K^- nuclear scattering have been used to extract the imaginary part of the forward amplitude (again assuming charge symmetry), which is then compared with the magnitude of the regeneration amplitude, also an absolute measurement.[5] The regeneration phase is thereby determined, to within a sign. Clearly, the indirect nature of such phase determinations may lead to systematic errors whose magnitude is difficult to estimate.

The first direct measurement of the regeneration phase was made by Bott-Bodenhausen *et al.*[6] They utilized the fact that the $\Delta S=\Delta Q$ rule permits only the decays $K^0 \to \pi^- l^+ \nu$ and $\bar{K}^0 \to \pi^+ l^- \bar{\nu}$. Therefore, as a K_2^0 beam passes through material and a new admixture of K^0 and $\bar{K}^0$ is created, a charge asymmetry among the leptonic decay products results. This charge asymmetry has a damped sinusoidal dependence on the proper time downstream from the regeneration material. The period of the sinusoid is characterized by the K_1^0-K_2^0 mass difference, and its starting phase is related to the regeneration phase. Depending on the regenerator the charge asymmetry can be made as large as 10–20%. This same method was substantially extended by Bennett *et al.*,[7] who, however, did not have sufficient resolution, using only scintillation counters, to allow a full kinematic reconstruction of each decay event. As will be shown later, the ability to reconstruct each event in the present experiment enables one to distinguish, in a statistical sense, between the various scattering processes, coherent, diffractive, and inelastic, which contribute differently to the charge asymmetry.

The principal thrust of this experiment was to measure the proper-time distribution of the charge asymmetry of the K_{e3} decay mode downstream from a regenerator and *concurrently* measure the structure in proper time of the 2π decay rate. To a first approximation, the phase difference of the two structures yields $\arg\eta_{+-}$. By performing both measurements in the same apparatus at the same time, one can hope to minimize many of the systematic errors which frequently occur when information is obtained by combining the results of independent experiments which measure different quantities under widely varying conditions. A particular example of cancellation of possible systematic errors in the present K_{e3} and $K_{\pi 2}$ measurements is the insensitivity to the K_1^0-K_2^0 mass difference. Since the δ dependence is similar in the phases of the two decay modes, the sensitivity of $\arg\eta_{+-}$ to δ is very weak. In contrast, an alternative method[8,9] for the measurement of this quantity, based on the interference in the $K_{\pi 2}$ decay mode of the K_1^0 and K_2^0 components of an initial K^0 beam, exhibits a strong mass-difference dependence (3° per 1% change in δ). This level of precision in δ has been achieved only in completely independent experiments.[1-3]

II. APPARATUS

The experiment was performed at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory. Included in the experimental program was a measurement of the K_1^0-K_2^0 mass difference which has been described previously.[3] The experimental arrangement, consisting of a neutral beam and a magnetic spectrometer with wire-plane spark chambers, was substantially the same as that used in the mass-difference experiment. Here we will emphasize only the features especially important for this measurement.

In Fig. 1 is shown the layout of the spectrometer, along with the three regenerator positions at which regenerator data were accumulated. Veto counter $\bar{A}$ moved with the regenerator. Comparable amounts of free decay data were taken with counter $\bar{A}$ at the 24-in. and 52-in. positions. Nominally the over-all coincidence-anticoincidence $\bar{A}\cdot E\cdot\bar{H}\cdot F_L\cdot F_R\cdot B_L\cdot B_R\cdot\bar{K}$ (where the bar denotes an anticoincidence) was required to trigger the spark chambers. For a majority of the run, the selectivity of the trigger for the K_{e3} and $K_{\pi 2}$ decay modes was enhanced, respectively, by the additional requirement of a Čerenkov signal or by rough restriction of the pion transverse momentum. The latter requirement was accomplished through appropriate coincidences between an additional coarse-grained hodoscope[10] supplementing the back hodoscope, B_L and B_R, and the front hodoscope, F_L and F_R.

The precise measurement of the K_{e3} charge asymmetry required a clean, charge-symmetric identification of that decay mode. Charge symmetry was ensured by ~500 field reversals during accumulation of data. Since the apparatus was designed to possess full symmetry about the beam line, the field reversals were needed only to cancel any small residual bias. A K_{e3} signature was provided by the threshold Čerenkov counter, containing CO_2 at atmospheric pressure. With a muon threshold of 3.5 GeV/c, it was sensitive, in the momentum range of this experiment, only to electrons. A simple and compact design was made possible by efficient detection of the Čerenkov light radiated over a relatively short (28-in.) path length. The light was focused by spherical acrylic front-surface mirrors [11] onto 5-in. photomultipliers [12] with bialkali photocathodes and extended UV sensitivity. The effective photocathode area was multiplied by additional front-surface glass mirrors lining pyramidal light pipes.

To maintain freedom from charge-dependent bias, it was especially important that the Čerenkov performance be uncorrelated with the magnetic field direction. The placement of the counter upstream of the magnet made possible three features designed to remove this kind of bias. First, the phototubes were naturally located away from the magnet to minimize the magnetic shielding problem. Second, the phototubes lay in the median horizontal plane of the magnet, ensuring, by symmetry, the absence of any fringe field component along their axes, a component that is extremely difficult to shield. Finally, the particles producing the background counting rate had trajectories which were affected by only the fringe field of the magnet rather than by the full field integral, as is the case when the counter is downstream of the magnet. Many tests demonstrated a negligible effect of magnet polarity on Čerenkov counter performance.

III. ANALYSIS

A. K_{e3} Analysis

The analysis of the K_{e3} decay mode is substantially more complex than that of the $K_{\pi 2}$ mode since only two of the three decay products are measured. The individual decay events can be fully reconstructed, to within the well-known twofold momentum ambiguity, if the K direction can be assumed to be the same as that of the unscattered beam. With the K direction not reconstructed, it is impossible, on an event-by-event basis, to separate the data originating from incoherently scattered K's from the data originating from strictly forward-going particles, i.e., the coherently scattered or unscattered K's. However, the kinematic information about each event is sufficient to obtain a statistical separation of data into subsets of varying enrichment of forward-going particles. This allows the use of an extrapolation procedure that extracts the values of the parameters for the case of coherent regeneration.

The regeneration phase was obtained from the observed K_{e3} asymmetry according to the following considerations. We have mentioned that the passage of the K_2^0 beam through material creates an asymmetry between the K^0 and $\bar{K}^0$ components, accompanied by a charge asymmetry in the K_{l3} decays because of the $\Delta S = \Delta Q$ rule. In general, if we take $a(\tau)$ to be the ratio of (mutually coherent) K_1^0 to K_2^0 amplitudes at a proper time τ, the asymmetry between the e^+ and e^- rates is given by

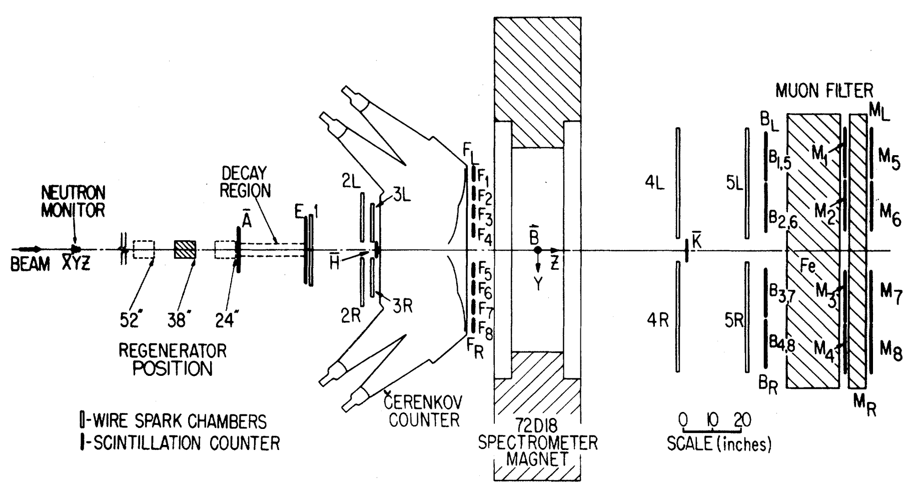

FIG. 1. View of spectrometer, showing magnet, wire spark chambers, trigger counters, Čerenkov counter, and regenerator.

$$R=(N^+-N^-)/(N^++N^-)$$
$$=\frac{(1-|x|^2)2\,\mathrm{Re}(a(\tau)+\epsilon)}{|1-x|^2-4\,\mathrm{Im}x\;\mathrm{Im}(a(\tau)+\epsilon)}\,. \quad (1)$$

Here

$$x=\frac{\text{amplitude}(\bar K^0\to\pi^-e^+\nu)}{\text{amplitude}(K^0\to\pi^-e^+\nu)}$$

parametrizes the departure from the $\Delta S=\Delta Q$ rule, and ϵ parametrizes the departure of

$$K_1^0=\frac{(1+\epsilon)K^0+(1-\epsilon)\bar K^0}{[2(1+|\epsilon|^2)]^{1/2}}$$

and

$$K_2^0=\frac{(1+\epsilon)K^0-(1-\epsilon)\bar K^0}{[2(1+|\epsilon|^2)]^{1/2}}$$

from pure CP eigenstates. Equation (1) has been carried to second order in the quantities a and x, with ϵ a very small perturbation. In the case of coherent regeneration of K_1^0's from a K_2^0 beam, we identify

$$a(\tau)=\rho e^{-(i\delta+1/2)\tau}\,,$$

where ρ is the coherent regeneration amplitude. The exponential factor expresses the attenuation of the K_1^0 amplitude by decay and its shift in phase, relative to the K_2^0 amplitude, τ K_1^0 mean lives downstream of the regenerator. Equation (1) becomes

$$R(\tau)=\frac{2(1-|x|^2)[\,|\rho|e^{-\tau/2}\cos(\varphi_\rho-\delta\tau)+\mathrm{Re}\epsilon]}{|1-x|^2-4|\rho|\,\mathrm{Im}x\,e^{-\tau/2}\sin(\varphi_\rho-\delta\tau)}\,. \quad (2)$$

For the case of purely coherent regeneration, Eq. (2) has the essential feature that the regeneration phase φ_ρ is determined by the damped sinusoidal K_{e3} asymmetry independent of all other nuclear parameters.

The contribution of diffractive effects to the observed K_{e3} asymmetry is readily understood by examination of the mathematical form of the asymmetry. Equation (1) emphasizes the fact that, by measuring an asymmetry in rates, one is sensitive to the ratio of the K_1^0 to K_2^0 *amplitudes*. This ratio is the basic quantity of interest for any of the mutually incoherent scattering processes which may occur. When events arising from a number of independent scattering processes are combined, the resulting asymmetry is the sum of a collection of damped sinusoids, each with different amplitudes and phases, weighted by the fractional population of each process. Accordingly, mutually incoherent types of diffraction and regeneration appear in the asymmetry formula to have regeneration amplitudes which add, as if the processes were coherent.

For a slab of thickness L, the coherent regeneration amplitude ρ is given by

$$\rho=\frac{i\pi N\Lambda[f(0)-\bar f(0)]}{k}\left\{\frac{1-e^{-(i\delta+1/2)L/\Lambda}}{i\delta+\frac12}\right\}\,,$$

with N the number density of nuclei, Λ the K_1^0 mean decay length, k the K_2^0 wave number, and $f(0)$ $[\bar f(0)]$ the forward scattering amplitude for K^0 $(\bar K^0)$ on Cu nuclei. The K_2^0 decay probability has been neglected, as has regeneration of K_2^0 from K_1^0. Because the factor in curly brackets varies with regenerator thickness, it is conventional to give results for φ_ρ in terms of the regeneration phase φ_f of a thin regenerator,

$$\varphi_f=\arg[i(f(0)-\bar f(0))]\,.$$

A fraction

$$F=1-e^{-NL\sigma_D}$$

of the K_{e3} decays are produced by K's which have been diffractively scattered by the Cu nuclei, where σ_D is the diffractive scattering cross section. The regeneration amplitude for this process is[13]

$$\rho'=\rho\left(1-\frac{2}{1-e^{-NL\sigma_D}}\frac{\sigma_D}{\sigma_T}e^{-i\varphi'}\cos\varphi'\right)\,, \quad (3)$$

with

$$\varphi'=\arg[(f(0)+\bar f(0))/i]$$

and σ_T the total cross section. The second term in (3), arising from the regenerative amplitude $[f(\theta)-\bar f(\theta)]$, has been simplified with application of the optical theorem and with the assumption

$$r(\theta)=\frac{f(\theta)-\bar f(\theta)}{f(\theta)+\bar f(\theta)}$$
$$=r(0)\,. \quad (4)$$

(We discuss this assumption below.) Following the above prescription, the effective regeneration amplitude a including both the coherent and diffractive amplitudes becomes

$$a(0)=(1-F)\rho+F\rho'$$
$$=\rho\left(1-2\frac{\sigma_D}{\sigma_T}\zeta e^{-i\varphi'}\cos\varphi'\right)\,, \quad (5)$$

where ζ is a correction factor introduced to express apparatus discrimination against multiple scattering.

A final contribution to the observed regeneration amplitude comes from the inelastic interaction of K_2^0's with the Cu nuclei. This effect is observed[14] in the $\pi^+\pi^-$ decay mode as a wide-angle tail in the distribution of regenerated K_1^0's. Because many inelastic channels may contribute, we elect to leave the magnitude and phase of the inelastic regeneration amplitude, relative to ρ, as free parameters in the fit. Independent consideration of the K's scattered at wide angle also removes from the approximation in Eq. (4) that class of events for which it is least satisfactory. For transverse momenta typical of nuclear diffraction, an optical-model calculation indicates that Eq. (4) is accurate to better than 5%. The contributions of different scattering processes to the observed regeneration amplitude are summarized by the vector diagram in Fig. 2, where it is seen that, for $\varphi' > 0$, the measured phase is moved toward the imaginary axis from the true regeneration phase.

A total of 1 458 118 events with K_{e3} signature have survived the event reconstruction. Each event has a minimum of five geometrical constraints on its track reconstruction, in addition to agreement with the condition of the trigger counters. Of the total, 571 438 decays occurred without a regenerator present, while 886 680 took place downstream of a 9 $\frac{1}{8}$-in. Cu regenerator with downstream end 24, 38, or 52 in. upstream of the end of the decay region (Fig. 1). Since the results are highly consistent for all three regenerator positions, we shall discuss the combined data. Figures 3(a) and 3(b) show that a strong proper-time-dependent asymmetry occurred in the presence of the regenerator. In its absence, the residual charge asymmetry

$$R_0 = 0.0038 \pm 0.0014$$

was consistent with that obtained in experiments[15] designed to measure Reϵ. However, for the purpose of making a combined correction for apparatus asymmetry and for Reϵ, only this above value of R_0 has been used.

Figure 3(c) shows the ratio of total K_{e3} decay

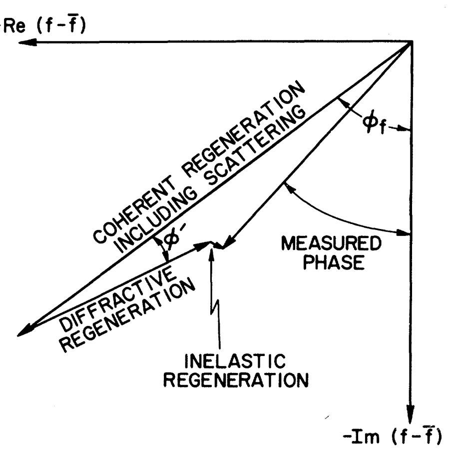

FIG. 2. Vector diagram showing the effective $(f(0) - \bar{f}(0))$ in the K_{e3} mode. The corrections arise from diffractive and inelastic regeneration.

rate for the 38-in. regenerator position to that for the 52-in. position. Here the proper time was zeroed for both cases at a fixed point in space just downstream of the 38-in. regenerator position, rather than at a fixed distance from the regenerator. The data from the 52-in. position, because of the damping of the K_1^0 amplitude, normalize the dependence on proper time. As seen in the denominator of Eq. (2), the proper time structure in the total decay rate provides a measure of the imaginary part of the $\Delta S = \Delta Q$ amplitude. The measurement yields a result of moderate precision,

$$\text{Im}x = 0.04 \pm 0.11.$$

Before discussing in detail the compensation for incoherent regeneration, we consider the correction made necessary by the twofold ambiguity in reconstructed K momentum. All of the proper times have been assigned using the average of the two solutions. On the other hand, to treat momentum-dependent effects, the data have been binned in the smaller of the two solutions, in order to

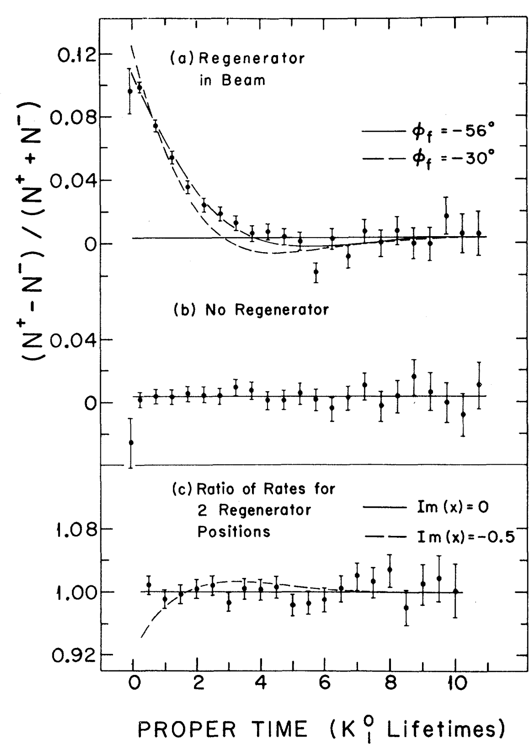

FIG. 3. Proper-time dependence of the K_{e3} charge asymmetry, (a) with and (b) without a 9$\frac{1}{8}$-in. Cu regenerator present. (c) The ratio of the proper-time distribution of the combined e^+ and e^- data taken with the regenerator at the near position to that taken at the far position. For part (c) the proper time has been zeroed at the near position for both distributions.

establish a firm lower-momentum limit for each bin. Since the intensity of K_2^0's decreases with increasing momentum, the low-momentum solution usually was more probable. Correspondingly, the mean value of the two solutions was, on the average, 7% higher than the true K momentum; the proper time was thereby systematically underestimated. A correction for this effect proceeded in three steps. In the first, a Monte Carlo calculation established the average relative probability of the high- and low-K-momentum solutions, as a function of their values. This probability was determined by the beam momentum and by the density of the Dalitz plot in the region of each of the solutions. These results were used in the next stage to create an array of probabilities for redistributing the events in their own and the neighboring proper-time bins. This was done as a function of the assigned proper-time bin and of the number n of bins by which the proper times, computed according to the low- and high-momentum solutions, would have been separated. Finally, a sample of events, with distributions in proper time and in n identical to those of the final data sample, were redistributed as described above, and the change in the fitted regeneration amplitude was computed. The process was iterated until the fit to the resulting asymmetry matched the fit to the data. This procedure was consistent with a general policy of asking only specific questions of the simulation routines, while using the data themselves to determine the corrections as much as possible. Over-all, the correction to the measured phase for the reconstructed momentum ambiguity was $-6.9°$, with a 5.4% attenuation of the amplitude of the asymmetry. The former result is very close to the $-7°$ shift in the phase at which the asymmetry crosses zero, obtained when the 7% difference between the true and the average of the high- and low-momentum solutions is used to correct the proper time.

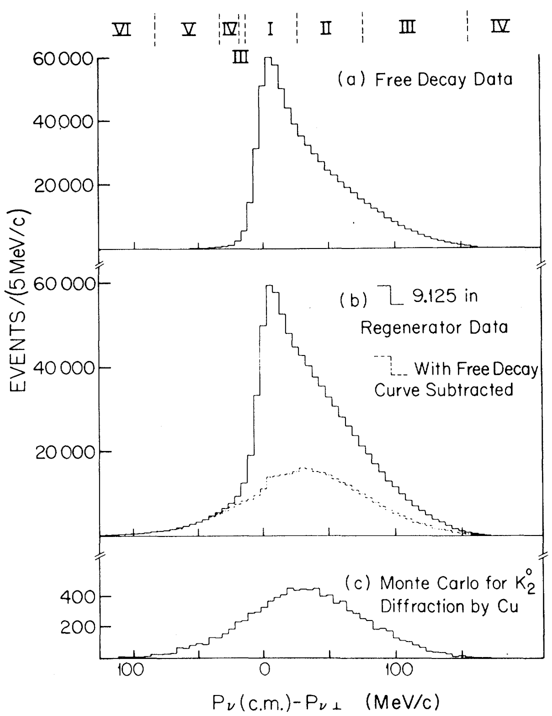

FIG. 4. Distribution in $\Delta_\nu = p_\nu\,(\mathrm{c.m.}) - p_{\nu\perp}$ for K_{e3} data taken (a) without and (b) with the regenerator present. The dashed curve in (b) shows the regenerator data after subtracting the (normalized) free-decay distribution. It is to be compared to the Monte Carlo prediction (c) for the distribution in Δ_ν of decays from diffractively scattered K's. Since the distribution in (c) is quite different from that in (a), the regions I–VI indicated at the top have varying contamination from incoherently scattered events, making possible an experimentally based correction for the effect.

An appreciable statistical separation of those events originating from K's which had been scattered in the regenerator from those which were undeflected was possible through the use of the variable

$$\Delta_\nu = p_\nu - p_{\nu\perp},$$

where p_ν ($p_{\nu\perp}$) is the momentum (transverse momentum) of the neutrino in the K^0 rest frame. As is seen in Fig. 4(a), a significant fraction of the events from undeflected K's had transverse neutrino momenta which were within ~30 MeV/c of their maximum value. Comparison of these data with the events recorded with the regenerator in place [Fig. 4(b)] confirms the Monte Carlo prediction in Fig. 4(c) that the scattering disperses this sharp peak, substantially changing the shape of the distribution. The range in Δ_ν has been divided into six regions, illustrated in Fig. 4 and enumerated in Fig. 5, which are populated with widely varying density by the scattered and unscattered data. For example, the diffractively regenerated data represent a three-times-larger fraction of the total in regions IV and V than in region I, while the inelastic regeneration is 30 times stronger in region VI than in region I.

As a basic fitting procedure, the factor ζ in Eq. (5) has been calculated for each Δ_ν region to take into account the relative population of scattered events. The effective regeneration amplitude has been applied to Eq. (2) (neglecting the Im x term) to predict the form of the asymmetry for a particular choice of the phase φ_f and magnitude of $f(0) - \bar{f}(0)$. Since there is a correlation between Δ_ν and the difference between high- and low-momentum solutions, the additional correction for the momentum ambiguity, outlined above, has been made in each of the Δ_ν regions. Finally, the predicted asymmetries have been compared to the data in the Δ_ν regions, and the χ^2 calculated.

In the scattering corrections, the following nuclear parameters have been used at 2.5 GeV/c:

$$\sigma_D/\sigma_T = 0.277 \pm 0.009,$$

$$\varphi' = 10° \pm 3°.$$

The former value is based primarily on two auxiliary measurements of σ_T,[16] and on the angular distribution of K_1^0's regenerated by a $\frac{3}{8}$-in. Cu regenerator; the optical theorem also is applied. A second evaluation has come from the comparison of σ_T to the absorption cross sections for K^+ and K^- in Cu measured by Cool *et al.*[17] The parameter φ' has been evaluated by measuring the ratio of coherent to incoherent $K_1^0 \to \pi^+\pi^-$ decays downstream of a $9\frac{1}{8}$-in. Cu regenerator, extrapolated to the forward direction. As originally pointed out by Good,[18] this ratio is independent of nuclear parameters for thin regenerators. However, for thick regenerators, a near cancellation of incoherent regeneration amplitudes of the type in Eq.

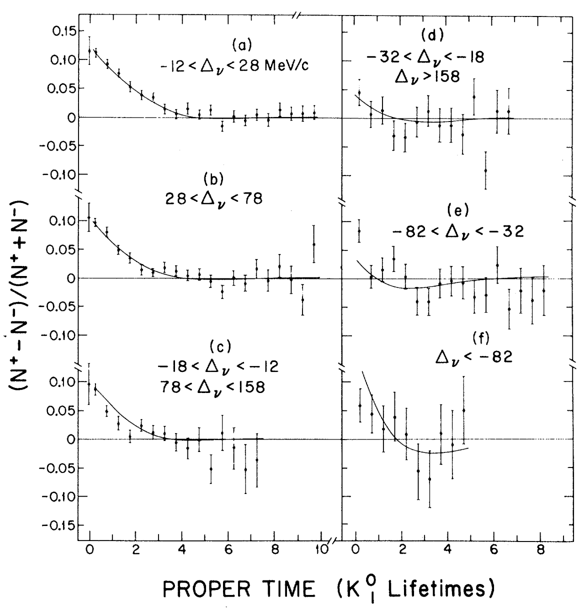

FIG. 5. Proper-time distribution of the K_{e3} charge asymmetry for six regions of Δ_ν. (a) is the richest in coherently scattered events, followed by (b) and (c). (d) and (e) are dominated by diffractively scattered events, while (f) is rich in those which have been inelastically scattered. Proceeding from (a) to (c), the asymmetries cross zero at progressively earlier times. This indicates the necessity for a negative correction to the regeneration phase observed in the combined data. The solid lines represent the best over-all fit to the data, with a correction for incoherent scattering appropriate to each Δ_ν region.

(3) occurs, giving a reasonable sensitivity to φ'. These values of σ_D/σ_T and φ' are in close agreement with an optical-model calculation with a wide choice of input parameters. It should be noted that all of the corrections and fits performed in the K_{e3} analysis have been done as a function of K momentum. In the case of the nuclear parameters, the optical-model calculations have served as a guide to the momentum dependence.

The result of the over-all fit to the regeneration phase is

$$\varphi_f = -56.2° \pm 5.2°$$

at 2.6 GeV/c, with a χ^2 of 515 for 463 degrees of freedom. In this fit the inelastic regeneration amplitude and phase, as well as the magnitude of the coherent regeneration amplitude, have been treated as free parameters. The error includes the correlation with the uncertainties in these quantities, in addition to the errors in the nuclear parameters and in the free-decay asymmetry. If no correction for incoherent scattering is made, the result is

$$\varphi_f(\text{uncorrected}) = -41.6° \pm 3.9°.$$

Therefore, a correction

$$\Delta\varphi_f(\text{scattering}) = -14.6° \pm 3.4°$$

is due to the effects of incoherent regeneration. It can be seen in Fig. 5 that the incoherent scattering does indeed produce this type of shift. Moving from Fig. 5(a) to the Δ_ν regions with greater contamination from incoherent scattering, the asymmetries cross zero at progressively earlier proper times. In the fit, the inelastic regeneration accounts for 40% of $\Delta\varphi_f$.

B. $K_{\pi 2}$ Analysis

To measure the regeneration phase using the charge asymmetry in the K_{e3} decay mode, it is desirable to make the ratio ρ (the regeneration amplitude) as large as possible. For $9\frac{1}{8}$ in. of Cu, $|\rho| \sim 0.1$. In the $K_{\pi 2}$ decay mode where the interference between the regeneration amplitude and η_{+-} is measured, the largest effects occur when $|\rho|$ is comparable to $|\eta_{+-}| = 1.9 \times 10^{-3}$. This apparent incompatibility for the $K_{\pi 2}$ interference part of the experiment with the requirements for the K_{e3} charge asymmetry measurement was handled in the following way. As noted earlier, a portion of the data was collected with the $9\frac{1}{8}$-in. Cu regenerator 52 in. from the end of the decay volume ("far" position), and another portion with the regenerator 38 in. from the end of the decay volume ("near" position). In both cases we considered only the $K_{\pi 2}$ decays occurring downstream of the 38-in. position, which was arbitrarily defined as the zero point in proper time. With the regenerator in the near position, $|\rho|$ is large compared to $|\eta_{+-}|$ and little interference is present. With the regenerator in the far position, however, the regenerated K_1^0 amplitude is attenuated through decay in the intervening drift space and maximum interference effects occur downstream of the 38-in. point. The near-position data served, therefore, to effectively normalize the far-position data. This normalization procedure compensates for any variation in detection efficiency through the decay volume. The $K_{\pi 2}$ decays originating from the regenerator in its far position and upstream of 38 in. did not, therefore, contribute to the final data sample. However, the K_{e3} charge asymmetry data were drawn from the full decay region behind the regenerator in both positions. Another part of the $K_{\pi 2}$ data was taken with various thin regenerator configurations. These regenerators (alternatively $\frac{1}{4}$ in., $\frac{3}{8}$ in., and 1 in.) were situated upstream of counter $\overline{A}$, set at 24 in. from the downstream end of the decay volume. Periodically they were replaced with a $9\frac{1}{8}$-in. regenerator to provide normalization. The results for the $K_{\pi 2}$ interference from the thin regenerator data are consistent with those obtained for the $K_{\pi 2}$ interference downstream of a $9\frac{1}{8}$-in. regenerator ("far-near" configuration). Thereby, still another check on possible systematic biases is provided. We present here only the results from the latter data because they dominate statistically.

The level of precision sought in this experiment requires especially careful attention to the problem of isolating the 2π decays originating from undeflected K's, which include the coherently regenerated K_1^0's and unscattered K_2^0's. After a cut on the invariant mass m^* of the two pions, $484 < m^* < 512$ MeV, the background was evaluated from the distribution of events in t, the square of the momentum transfer to the regenerator. The usual technique is to assume an exponential dependence of the background on t and extrapolate the background level found at large t to the region of the forward peak. While the diffractive scattering is justifiably treated in this way, the contamination from the $K_{\mu 3}$ decay mode (the K_{e3} contamination is removed by the Čerenkov signature) is not exponential in t, and, furthermore, is sensitive to the mass cut. Moreover, the relative amounts of $K_{\mu 3}$ background and diffractive scattering vary over the proper-time intervals measured in this experiment. Consequently the background subtraction directly influences the main problem of the $K_{\pi 2}$ portion of the experiment, i.e., the determination of the forward 2π rate as a function of proper time. The $K_{\mu 3}$ background was subtracted by first normalizing the number of free-decay $K_{\mu 3}$'s to the number of unscattered $K_{\mu 3}$'s observed behind the regenerator. This normalization was done using the relative number of events for the two samples of data in the region of invariant mass 360–430 MeV, well outside the K^0 mass, and correcting with the known ratio of scattered to unscattered K_2^0's behind the regenerator. The normalized t distributions for the free-decay data were then subtracted from the corresponding distributions obtained with the regenerator in place. The remaining background events in the t distribution of regenerator data were then fitted to an exponential and the subtraction performed as usual.

As an independent check on the above procedure, the background was subtracted by a second method. The shape of the undeflected $K_{\pi 2}$ forward peak in the t distribution was obtained from the data at small proper time where the background was minimal. The shape of the $K_{\mu 3}$ t distribution was deduced from a Monte Carlo calculation. Using the known ratio between the number of incoherently regenerated K_1^0's and $K_{\mu 3}$'s, a relatively short extrapolation in t could be used. In particular the background was evaluated at $480 > t > 240$ (MeV/c)^2 and extrapolated to $240 > t > 0$ (MeV/c)^2. The t distributions were well typified by those already published[3] and are not reported here. The final results, using the two completely independent background-subtraction procedures, agree to within 1°.

The data were separated into 5 momentum bins over the region $1.5 < p < 4$ GeV/c and 12 proper time bins each of width $\frac{1}{2}\tau_1$. After background subtraction, the ratio of the number of 2π events observed in the far position of the regenerator to the number in the near position was evaluated for each momentum and proper-time bin. In each momentum interval this ratio was then fitted, using least mean squares, to the function

$$F(\tau)=\frac{|\eta_{+-}|^2+\rho^2 e^{-(\tau+\tau_0)}+2|\eta_{+-}|\,|\rho|\,e^{-(\tau+\tau_0)/2}\cos(\varphi_{+-}-\varphi_\rho+\delta(\tau+\tau_0))}{|\eta_{+-}|^2+\rho^2 e^{-\tau}+2|\eta_{+-}|\,|\rho|\,e^{-\tau/2}\cos(\varphi_{+-}-\varphi_\rho+\delta\tau)},$$

where τ_0 is the proper-time interval between the two regenerator positions (e.g., $\tau_0 = 2.75$ at 2.5 GeV/c). The background-subtraction procedure which employs the free-decay data subtracts events arising from $|\eta_{+-}|^2$ terms. These terms were not included in the expression for $F(\tau)$ when the data with free-decay subtraction were fitted. $F(\tau)$ was averaged over the momentum band by weighting with the observed momentum spectrum for the 2π decay events. Values for η_{+-}, ρ, and δ were derived from external sources. We have taken $|\eta_{+-}| = (1.95 \pm 0.03)\times 10^{-4}$ and $\delta = -0.465 \pm 0.004$, and have calculated ρ (a function of momentum) from published data[19] on $(f - \bar{f})$ as well as the data acquired in the K_{e3} part of this experiment. We emphasize that the result is extremely insensitive to $|\rho|/|\eta_{+-}|$. A 10% variation in this ratio leads to a change in the measurement of $\varphi_{+-} - \varphi_\rho$ by less than 3% of the statistical error. The final result is also highly insensitive to δ over the range of its accepted error.

As an illustration of typical data we show in Fig. 6 the proper-time distribution of the events taken at the near regenerator position in the K momentum interval 2.4–3.0 GeV/c, which, as we have noted, is governed primarily by the K_1^0 lifetime and by the detection efficiency of the apparatus. Figure 7 shows the time distribution of the ratio between far and near regenerator data in the same momentum interval with the best-fit curve, $\varphi_{+-} - \varphi_f = 89.5°$, given by the solid line. Fits 5.7° to either side of the optimum are also shown.

IV. RESULTS AND CONCLUSIONS

The particular strength of the experimental approach used here has been the ability to measure concurrently all of the quantities needed for determination of the η_{+-} phase. Since the phases obtained from the K_{e3} asymmetry and from the $K_{\pi 2}$ interference have been combined, the possibility of systematic error is minimized. It is of interest, nevertheless, to compare the individual phases obtained in this measurement to those from other experiments.

The result of this experiment for the regeneration phase in Cu at 2.6 GeV/c is[20]

$$\varphi_f = -56.2° \pm 5.2°.$$

This value includes a significant correction for diffractive and inelastic scattering, viz.,

$$\varphi_f(\text{uncorrected}) = -41.6° \pm 3.9°,$$

$$\Delta\varphi_f(\text{incoherent}) = -14.6° \pm 3.4°.$$

The other direct measurement of this phase has yielded the result[7]

$$\varphi_f(\text{uncorrected}) = -44.4° \pm 7.3°.$$

To this value the authors of Ref. 7 applied a $-4.5°$ correction for incoherent scattering, using the assumption that only diffractive effects need be included and that $\bar{f}(0)$ is purely imaginary. We emphasize that the correction for incoherent scattering reported here has been determined primarily by examination of the data themselves, under conditions of varying enrichment of the coherently scattered events.

Despite the ambiguity in reconstruction, it has been possible to divide the K_{e3} results in Table 1(a) into four partially overlapping K momentum bands, along with the individual results for φ_f and

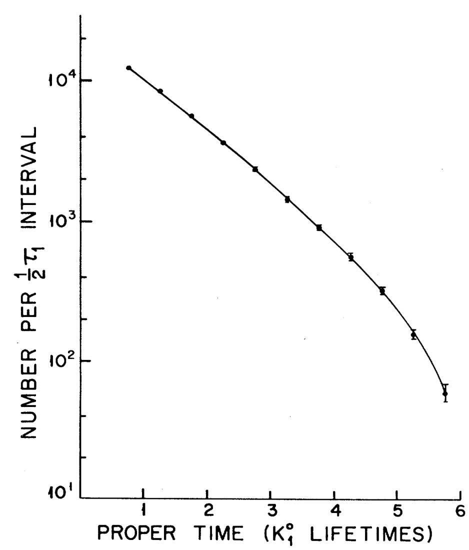

FIG. 6. Proper-time distribution of $K_{\pi 2}$ events in the momentum interval 2.4–3 GeV/c, collected with the $9\frac{1}{8}$-in. regenerator in its near position.

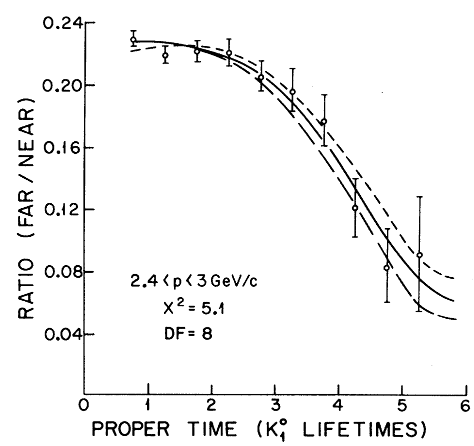

FIG. 7. Proper-time distribution of the ratio between far- and near-regenerator data, for events in the momentum interval 2.4–3 GeV/c. The solid line gives the best-fit curve, $\varphi_{+-} - \varphi_f = 89.5°$, and the dashed lines give fits 5.7° to either side of the optimum.

$(1-|x|^2)|f(0)+\bar{f}(0)|/k|1-x|^2$. The results are consistent with a constant regeneration phase and a slowly falling $|f-\bar{f}|/k$ over the K momentum range 1.2–4 GeV/c. Recently, precise K_{l3} data have been reported[21] which are consistent with exact $\Delta S=\Delta Q$ selection; taking $x=0$ and averaging over the entire momentum range of the present data, we obtain $|f(0)-\bar{f}(0)|/k=26.1\pm1.1$ mb at an average momentum of 2.6 GeV/c.

Analysis of the $K_{\pi 2}$ data yields (at the same average momentum)

$$\varphi_{+-}-\varphi_f=94.0°\pm2.5°.$$

This result is particularly insensitive to the value of $|f(0)-\bar{f}(0)|$ and is the same for two independent methods of background subtraction. The result for each of five momentum bands is shown in Table I(b); no substantial momentum dependence is evident. Agreement with other measurements[22,23] of the phase in this momentum range is good, with the present results dominating statistically. The results for φ_f and for $(\varphi_{+-}-\varphi_f)$ are exhibited as a function of momentum in Fig. 8, with the same curve (a fitted second-order polynomial in $1/p$) drawn through each set of points.

Combining the K_{e3} and $K_{\pi 2}$ data by subtracting the two curves in Fig. 8 yields the final result

$$\varphi_{+-}=36.2°\pm6.1°.$$

This result is not exactly the same as that obtained by combining the two momentum-averaged phases, because of the slightly different momentum distributions of K_{e3} and $K_{\pi 2}$ data. For comparison, the results of the two "vacuum regeneration" experiments[8,9] combined with the average of three recent measurements[1-3] of the K_1^0-K_2^0 mass difference yield

$$\varphi_{+-}=41.2°\pm4.9°.$$

Any theory (such as the superweak model) limiting CP noninvariance to imaginary off-diagonal terms in the self-energy matrix would require

$$\varphi_{+-}=-\tan(2\delta)=42.8°.$$

Although the central value reported here is not the same, the size of the error prevents us from ruling out this possibility. It should be recognized, however, that experimental bounds on CP noninvariance in the individual decay channels have not yet ruled out a phase difference of order 0.1 rad from the superweak value.

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TABLE I. Dependence of measured phases on kaon momentum.

(a) K_{e3} results

$\langle p_K\rangle$ (GeV/c)	φ_f (deg)[a]	$(1-\lvert x\rvert^2)\lvert f(0)-\bar{f}(0)\rvert/k\lvert 1-x\rvert^2$ (mb)[b]
1.7	-56.4 ± 16.0	27.1 ± 4.9
1.9	-72.5 ± 10.0	29.2 ± 2.6
2.2	-55.8 ± 8.5	27.3 ± 2.0
3.0	-54.5 ± 5.9	25.1 ± 1.0

(b) $K_{\pi 2}$ results

p_K range (GeV/c)	$(\varphi_{+-}-\varphi_f)$ (deg)
1.5–1.9	114.5 ± 17.5
1.9–2.4	96.0 ± 3.5
2.4–3.0	89.5 ± 4.0
3.0–3.7	91.6 ± 8.5
3.7–4.5	90.0 ± 20.0

[a]An additional over-all error of ±3.4° applies to these values.

[b]An additional over-all error of ±0.7 mb applies to these values. The additional errors correspond to those systematic uncertainties which are momentum-independent.

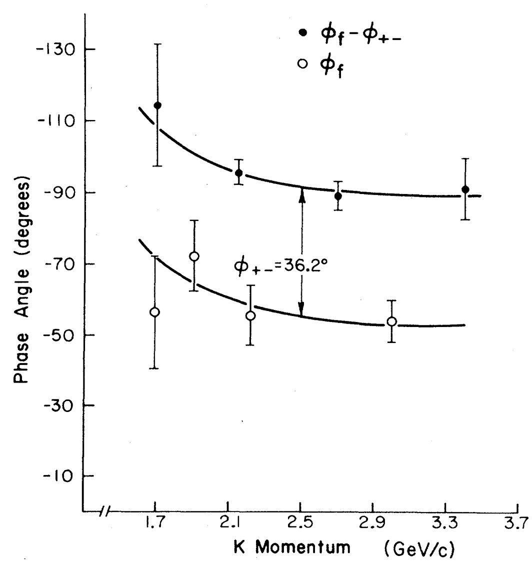

FIG. 8. Momentum dependence of the K_{e3} results for φ_f, and the $K_{\pi 2}$ results for $\varphi_f-\varphi_{+-}$. Subtraction of the two curves gives $\varphi_{+-}=36.2°\pm6.1°$.

tion of the apparatus and the accumulation of data. A strong and continuing contribution to the experiment's success was made by V. M. Bearg and A. David, for which we are especially grateful. The experiment was expedited through the cooperation of the Fiat Motor Company, Torino, Italy, who made their computer facility available for part of the analysis.

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[10]We thank Professor Richard Wilson for the loan of the additional hodoscope counters, and Professor L. N. Hand and T. Loomis for designing and implementing the selective $K_{\pi 2}$ trigger.

[11]Purchased from Spartex, Inc., P. O. Box 437, Sparta, Wisconsin. The mirrors were manufactured for intended use as second-surface convex rearview mirrors on trucks.

[12]RCA-4522 photomultipliers.

[13]The derivation of Eq. (3) uses the techniques developed by R. H. Good, R. P. Matsen, F. Muller, O. Piccioni, W. M. Powell, H. S. White, W. B. Fowler, and R. W. Birge, Phys. Rev. 124, 1223 (1961).

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[16]In this experiment, we measured σ_T in Cu by observing the rate of $\pi^+\pi^-$ decays from K_1^0's regenerated by a thick regenerator, while varying the thickness of a second Cu absorber placed far upstream. We obtain $\sigma_T = 957 \pm 10$ mb at an average momentum of 2.7 GeV/c, and combine it with the value $\sigma_T = 940 \pm 20$ mb quoted in Ref. 7.

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[20]At first sight it would appear that this result for the regeneration phase is in disagreement with an earlier determination using the triangular method [V. L. Fitch, R. F. Roth, J. S. Russ, and W. Vernon, Phys. Rev. 164, 1711 (1967)]. The difference is probably explained by the fact that the earlier determination, where the phase was found to be $\pm(24°{}^{+12°}_{-24°})$, was for a different material (Be) and at a substantially different average momentum (1.6 GeV/c). In a particular optical-model calculation, a set of parameters which gives the measured phase in Cu at $\langle p \rangle = 2.6$ GeV/c is as follows: Fermi distribution of nucleon density, nuclear radius of $1.15A^{1/3}$ F, falloff parameter of 0.56 F, and ratio of the real to the imaginary forward scattering amplitude for positive and nega-

tive strangeness equal to −0.6 and −0.1, respectively. If these same parameters are applied to Be the computed phase is less negative by 9°. If, in addition, the momentum is reduced with no change in the relative value of the real parts, the computed phase shifts another +11°, giving a total phase shift of +20°. Since at the lower momenta a resonance is approached, it is entirely reasonable that the remaining discrepancy arises from a change in the ratios of real to imaginary amplitudes, to which the regeneration phase is highly sensitive.

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Inelastic K^+p Reactions at Incident Momenta from 1.37 to 2.17 GeV/c*

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Inelastic K^+p reactions have been studied in a 400 000-picture exposure of the LRL 25-in. hydrogen bubble chamber. Cross sections have been obtained for single-pion and two-pion final states corresponding to the two-prong-V and four-prong topologies. These channels show a smooth energy dependence, consistent with observations at other momenta. The production and decay angular distributions for the quasi-two-body channels agree with the predictions of simple exchange models and show no evidence of an s-channel resonance. It is not possible, however, to place any quantitative limit on the production of a Z^*. Quark-model relations for double-resonance production have been tested and are well satisfied by our data.

I. INTRODUCTION

A number of recent experiments have suggested a possible Z^* resonance in K^+p scattering. The energy dependence of the total K^+p cross section[1] and of the total elastic cross section[2] are shown in Fig. 1. The total elastic cross section falls smoothly with momentum, but the total cross section data show a bump at 1.35 GeV/c and a shoulder at about 1.9 GeV/c. A fit to the bump suggests a resonance of 4 mb at a mass of 1910 MeV. The full width at half-height is 180 MeV and the value of $(J+\frac{1}{2})K$ is 0.3, where J is the spin and K is the elasticity. The shoulder corresponds to a 0.2-mb enhancement at 2190 MeV with a width of 120 MeV and $(J+\frac{1}{2})K=0.03$.

Analysis of the elastic differential cross section and polarization data also suggests a possible resonance.[3] Some of the solutions from both energy-dependent and energy-independent partial-wave analyses suggest a resonance in the $P_{3/2}$ partial wave at an incident momentum between 1.3 and 1.9 GeV/c. These analyses show that the resonance, if it exists, is very inelastic (elasticities vary between 0.1 and 0.45). They also indicate, however, that the speed (the rate of change of phase shift with energy) is not consistent with resonance behavior.

All experiments which show some resonance features share the common characteristic of a small elasticity. For this reason it is of interest to study the inelastic channels in the K^+p system. In an earlier experiment Bland *et al.*[4] studied single-pion production at incident momenta between 0.84 GeV/c and 1.37 GeV/c. He concluded that the first bump in the total cross section can be interpreted as a threshold effect, resulting from the opening of the inelastic channel $K\Delta$. There is no indication of a Z^* resonance over the momentum range of that experiment.

It is the purpose of this experiment to extend to higher energies the study of the inelastic K^+p reac-