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CP Violation, Neutral Currents, and Weak Equivalence

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Within the past few months two excellent summaries(1,2) of the state of our knowledge of the weak interactions have been presented. Correspondingly, we will not attempt a comprehensive review but instead concentrate this discussion on the status of CP violation; the question of the neutral currents, and the weak equivalence principle.

The Parameters

The phenomenon of CP violation has been definitely observed only in the neutral K meson system. It is a tiny effect but nevertheless, many of the parameters which characterize the violation have been determined with some crispness. It is not surprising that this phenomenon has yet to be seen in other systems since the neutral K system is so extraordinarily sensitive, several orders of magnitude more sensitive than any other system known. The searches for evidence of CP violation in other systems have been made in the fond hope that the small effect in the neutral K system was, in fact, a massive effect in some other channel. Unfortunately, they have been false hopes. The status of the searches for CP or T violation in other systems will be summarized later.

To date, 10 CP violating parameters in the neutral K system have been measured. However, some of these have yet to be measured to the accuracy necessary to make the result relevant to the immediate questions. These

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parameters are (we assume CPT invariance throughout),

$$\eta_{+-} = \frac{\text{Ampl } (K_L \to \pi^+\pi^-)}{\text{Ampl } (K_S \to \pi^+\pi^-)} \qquad \text{phase and magnitude}$$

$$\eta_{oo} = \frac{\text{Ampl } (K_L \to 2\pi^o)}{\text{Ampl } (K_S \to 2\pi^o)} \qquad \text{phase and magnitude}$$

$$\text{Re}\,\epsilon = \text{Re}\left[\frac{1}{3} (2\eta_{+-} + \eta_{oo}) \right]$$

$$\text{Imag } x' = \text{Imag } \frac{\text{Ampl } (K^o \to \pi^+\mu^-\nu)}{\text{Ampl } (K^o \to \pi^-\mu^+\nu)}$$

$$\text{Imag } x = \text{Imag } \frac{\text{Ampl } (K^o \to \pi^+e^-\nu)}{\text{Ampl } (K^o \to \pi^-e^+\nu)}$$

$$\eta_{+-o} = \frac{\text{Ampl } (K_S \to \pi^+\pi^-\pi^o)}{\text{Ampl } (K_L \to \pi^+\pi^-\pi^o)} \qquad \text{phase and magnitude .}$$

Imag ξ = Imag part of form factor ratio in $K_{\mu 3}$ decay

There remain several other parameters, e.g.

$$\eta_{ooo} = \frac{\text{Ampl } (K_S \to 3\pi^o)}{\text{Ampl } (K_L - 3\pi^o)} \quad ,$$

that have not been measured at all. As has been recognized for a long time, a convincing demonstration of a difference between η_{+-} and η_{oo} would be highly informative as far as diagnosing the ultimate source of CP violation. If, on the other hand, $\eta_{+-} = \eta_{oo}$ within the experimental errors, a wide range of possibilities remain.[3]

Eta Plus Minus

About the magnitude there is little question. Since the days of the initial observation the value has hovered around the current best value, viz.

$$|\eta_{+-}| = 1.95 \pm 0.03 \times 10^{-3} \quad .$$

The phase, as one might expect, is trickier to measure and its value has seen wilder oscillations. Three years ago a judicious summary[4] of the data available yielded arg $\eta_{+-} = \varphi_{+-} = 59^\circ \pm 6^\circ$. Now several independent measurements using different techniques lead to a different number but one in which one can have, hopefully, a fair amount of confidence. As examples of completely different techniques I will discuss the last two reported measurements. The first is that of the Chicago group working at Argonne.[5] They used so-called "vacuum regeneration" i.e. the fact that with CP violation the time structure in the $\pi^+\pi^-$ rate after production of a K^o should go as

$$I(\pi^+\pi^-) \;\alpha\; \left| e^{-(i\delta + 1/2)t/2\tau_S} + \eta_{+-} \right|^2$$

$$= e^{-t/\tau_S} + |\eta_{+-}|^2 + 2\,|\eta_{+-}|\, e^{-t/2\tau_S} \cos\left(\delta\left(\frac{t}{\tau_S}\right) + \varphi_{+-}\right) \cdot \qquad (1)$$

Interference is clearly seen in the region where the K_S^o and K_L^o amplitudes are roughly the same (i.e. where $e^{-t/2\tau_S} \cong |\eta_{+-}|$ or where $t \cong 12\ \tau_S$) and from it the phase $(\varphi_{+-} + \delta\ t/\tau_S)$ is determined. In the sensitive region,

$\delta\, t/\tau_S \cong 300^\circ$ so the technique is extremely sensitive to the K_L^o - K_S^o mass difference, $\delta = (m_L - m_S)\,\tau_S/\hbar$. The Chicago result is

$$\varphi_{+-} = 42.4^\circ + 310.0^\circ\ (1 - 0.538 \times 10^{10}\ \frac{\tau_S}{\delta}) \pm 4.0^\circ .$$

Fortunately, in the past year, three separate measurements of the mass difference have been made, each to about 1%, and they all agree!![6,7,8] The combined result is

$$\frac{\delta}{\tau_S} = 0.5390 \pm .0035 \times 10^{10}\ \text{sec}^{-1}$$

or

$$\frac{\delta}{\tau_S} = 858\ \text{Mc} \quad \text{(L band!)} \quad .$$

When doing interferometry with neutral K's it is convenient to remember that this mass difference leads to a phase shift between K_S^o and K_L^o amplitudes at the same energy of 26.4° per K_S^o mean life.

This value for the mass difference leads to

$$\varphi_{+-} = 43.0^\circ \pm 5.0^\circ \quad .$$

A group from Princeton[9] working at the A.G.S. have measured φ_{+-} in one self-contained experiment using a technique which is completely orthogonal to that described above. The interference effects between the $K_L \rightarrow \pi^+\pi^-$ and the $K_S \rightarrow \pi^+\pi^-$ amplitudes when the K_S^o's have been produced by coherent regeneration have been a powerful tool. The intensity of the forward going decays to $\pi^+\pi^-$ as a function of time τ measured in units of the K_1 mean life is

$$I\ (\pi^+\pi^-) = |\rho|^2\ e^{-\tau} + 2|\eta_{+-}||\rho|\ e^{-\tau/2}\cos\ (\delta\tau + \varphi_\rho + \varphi_{+-}) + |\eta_{+-}|^2\ . \tag{2}$$

Turning our attention to the 3-body leptonic decays and utilizing the $\Delta S = \Delta Q$ rule whereby $K^o \to \pi^- e^+ \nu$ and $\overline{K}^o \to \pi^+ e^- \nu$, the K_{e3} charge asymmetry behind a regenerator resulting from the decay of forward going K's has a time dependence given by:

$$A = \frac{N(e^+\pi^-\nu) - N(e^-\pi^+\overline{\nu})}{N(e^+\pi^-\nu) + N(e^-\pi^+\overline{\nu})} = 2\ |\rho|\ e^{-\tau/2}\cos\ (\varphi_\rho - \delta\tau) \tag{3}$$

where ρ is the K_S^o amplitude immediately behind the regenerator (with the 9 1/8" thick Cu regenerator used in this experiment $|\rho| \sim 0.1$). The main idea of the measurement was to compare, in the same apparatus with the data taken concurrently, the structure in proper time in the K_{e3} asymmetry and the $\pi^+\pi^-$ rate. The relative phase of the two structures yields φ_{+-}. The neatness of the above procedure is somewhat muddied by the fact that the K_{e3} decays originating from diffractively scattered K's exhibit an asymmetry almost opposite in sign to the coherently scattered. Furthermore the 3-body decay does not permit a clean separation of the decays originating from coherently scattered K's from those diffractively scattered. In fact, summing the scattering to all orders leads to an effective regeneration amplitude

$$\rho_{eff} = \rho\ (1 - 2\ \frac{\sigma_D}{\sigma_T}\ \zeta\ \cos\ \varphi'\ e^{-i\varphi'})\ . \tag{4}$$

where ζ is the relative apparatus efficiency for detecting the diffractively scattered K_L^0's and in $\varphi' = \arg[-i(f(0) - \bar{f}(0))]$ we have collected our ignorance of the scattering which we were originally trying to avoid. The σ_D/σ_T is the ratio of the diffraction to the total cross sections.

For the record we note that Eq. (3) is a simplification of the complete expression.

$$A(\tau) = \frac{2(1 - |x|^2)[|\rho|e^{-\tau/2}\cos(\varphi_\rho - \delta\tau) + \mathrm{Re}\,\epsilon]}{|1 - x|^2 - 4|\rho|e^{-\tau/2}\,\mathrm{Im}\,x\,\sin(\varphi_\rho - d\tau)} \qquad (5)$$

where $x = [(\Delta S = -\Delta Q)$ amplitude$/(\Delta S = \Delta Q)$ amplitude$]$. While it appears that the unavoidable presence of the diffractively scattered K^0's substantially dilutes the crispness of the original experimental plan, the data have been parameterized in such a way as to permit separation into varying degrees of enrichment of the forward scattered, coherent, component and thereby make possible an extrapolation to a zero diffractively scattered component. The separation parameter used was

$$\Delta = p_\nu\,(\mathrm{c.m.}) - p_{\nu\perp}$$

Figure 1 illustrates the effectiveness of the parameter Δ in separating the coherent from the incoherently scattered K's. Figure 2 shows that the fit to the asymmetry as a function of particular Δ bands. The K momentum accepted by this apparatus ranged from 1.2 to 4 BeV with a weighted mean of 2.6 BeV.

Whereas the asymmetry measurement is self-normalizing and the result is independent of the detection efficiency, the measurement of the interference in the 2π rate is not intrinsically self-normalizing. However, in this experiment, the data were made self-normalizing by recording them with the regenerator in two different positions. When the regenerator was in the "near position" to the volume in which the 2π decays were measured ($|\rho e^{-(i\delta + 1/2)\tau}| \gg |\eta_{+-}|$ throughout the pertinent volume) little interference was present and the data served mainly to calibrate the proper time dependence of the detection efficiency. In the "far" position, a proper time τ_0 upstream, $|\rho e^{-(i\delta + 1/2)(\tau + \tau_0)} \sim \eta_{+-}|$, the interference effects are maximized. The ratio of the proper time dependences at the far and near positions displays the interference effects independent of detection efficiency. The resulting phase comparison between the K_{e3} asymmetry and $K_{\pi 2}$ interference was done as a function of momentum. The difference, assuming it to be independent of momentum, is

$$\varphi_{+-} = 36.2^\circ \pm 6.0^\circ \quad ,$$

about one σ away from the "vacuum regeneration" result. The weighted mean of this result and that from "vacuum regeneration is $40.3^\circ \pm 3.9^\circ$. If one includes in the averaging all of the more recent data[10] one gets a somewhat higher number, viz.

$$\varphi_{+-} = 41.8^\circ \pm 3.0^\circ .$$

At this point it is appropriate to observe that the "natural" phase is

$$\arg\,(1/i\delta + 1/2) = 43.0^\circ + 0.4^\circ .$$

We have assumed throughout that $m_L > m_S$. This has recently been reconfirmed by a Carnegie Tech., BNL Case group[11] who conclude that $m_L > m_S$ is $\sim 10^5$ times more likely than the reverse.

Eta Nought Nought

The history of the attempts to measure η_{oo} has been turbulent for good reason. The rare decay of $K_L \to 2\pi^o$ competes with a dominant mode $K_L \to 3\pi^o$. The photons are difficult to measure because among the 6 γ's in the $3\pi^o$ mode, 2 are very likely to be going backward in the c.m. system. They, correspondingly, have very little energy in the laboratory, and are not easily detected. The other 4 photons carry the full energy of the K with only transverse components as signatures. In Fig. 3 we have collected the various results.[12,13,14,15,16,17,18,19,20] Since the rate is almost always the measured quantity we have plotted $|\eta_{oo}|^2$. Of special note is the result from the liquid Xenon chamber, Barmin et al.,[15] a truly monumental bubble chamber experiment, and the most recent result from CERN, Darriulat et al., reported at the Amsterdam conference.[19] Table I tabulates the data.

Clearly the results are not consistent -- and there is no apparent reason for rejecting any one measurement. A weighted average of all of the results leads to

$$|\eta_{oo}|^2 = 4.3 \pm 0.4 \times 10^{-6} \quad \text{internal errors}$$

$$= 4.3 \pm 0.7 \times 10^{-6} = \text{external errors.}$$

We subsequently use the number with the larger error.

Chollet, et al.,[17] have also studied the interference pattern in the

$2\pi^0$ rate behind the regenerator and arrive at $43.0^\circ \pm 19.0^\circ$ for the phase, a result, they emphasize, which is largely independent of the magnitude.

We have then, summarizing all the data

$$\eta_{oo} = 2.08 \pm 0.16 \times 10^{-3} \quad e^{i\, 43.0^\circ \pm 19.0^\circ}$$

$$\eta_{+-} = 1.95 \pm 0.03 \times 10^{-3} \quad e^{i\, 41.8^\circ \pm 3.0^\circ} \quad .$$

Except for some lingering reservations about $|\eta_{oo}|$ one can feel fairly comfortable about the four numbers.

Status of the Wu-Yang Triangle

We assume CPT and re-express the 4 parameters determined above in terms of those associated with the mass decay matrix,[21] viz.

$$\epsilon = \frac{2}{3}\,\eta_{+-} + \frac{1}{3}\,\eta_{oo} \qquad\qquad \epsilon = \frac{p - q}{p + q}$$

$$\epsilon' = \frac{1}{3}\,(\eta_{+-} - \eta_{oo}) \qquad\qquad \epsilon' = \frac{i \text{ Im } A_2}{2\sqrt{A_o}}\, e^{i(\delta_2 - \delta_o)}$$

where

$$K_L^o = [1/\sqrt{p^2 + q^2}][pK^o + q\bar{K}^o]$$

$$K_S^o = [1/\sqrt{p^2 + q^2}][pK^o - q\bar{K}^o] \quad .$$

Inserting the above information on η_{oo} and η_{+-} we have,

$$\text{Re } \epsilon' = -\ .03\,^{+.18}_{-.13}$$

$$\therefore \quad \text{Im}\ \epsilon' = -\ .03^{+.16}_{-.14}$$

with the errors correlated so that ϵ' is either in the first or third quadrant.

In short, $|\epsilon'|$ is not more than $\sim 20\%$ of $|\eta_{+-}|$. But tighter limits can be placed on arg ϵ' from our knowledge of the $\pi\pi$ phase shifts -- deriveable[22] from the $K^+ \to \pi^+\pi^0$ decay rate and the ratio

$$R = \frac{\Gamma(K^0_S \to \pi^+\pi^-)}{\Gamma(K^0_S \to 2\pi^0)} \quad .$$

A recently obtained[23,24] average for R yields $R = 2.22 \pm .03$, the departure from 2 being the contribution of the $T = 2$ amplitude given by

$$R = .986\ (2 + 6\sqrt{2}\ \text{Re}\ A^0_2/A_0\ \cos\ (\delta_2 \to \delta_0)) + \Delta_{em}$$

where Δ_{em}, the electromagnetic correction, has been estimated to be $\sim .006 \pm .04$.[25] One can, with good justification (invoking, e.g., the Cabibbo hypothesis), ignore possible $|\Delta I| = 5/2$ transitions, whereupon $A^0_2/A_0 = 2/3\ A^+_2/A_0$. From $K^+ \to \pi^+\pi^0$ decay we have $A^+_2/A_0 = .054$. We obtain then, $\cos\ (\delta_2 - \delta_0) = .63 \pm .16$ and

$$|\delta_2 - \delta_0| = 51.0^\circ \pm 12.0^\circ \quad .$$

The analysis of multipion production data has led to values of δ_0 with this same magnitude and in the first quadrant. With δ_2 small we use this information and take accordingly.

$$\delta_2 - \delta_o = -51.0^\circ \pm 12.0^\circ$$

whereupon the arg $\epsilon' = 39.0^\circ \pm 12.0^\circ$. Since arg ϵ' is close to arg η_{+-} the Wu Yang triangle tends toward a Wu Yang line. Inserting this new constraint we have

$$\epsilon' = -.04 \pm 0.06\, e^{i39.0^\circ \pm 12.0^\circ} \times 10^{-3}$$

and

$$\epsilon = 1.99 \pm 0.07\, 3^{i43.0^\circ \pm 3.0^\circ} \times 10^{-3} \quad .$$

Charge Asymmetry

Because with CP violation

$$K_L^o \cong (K^o + \overline{K}^o) + \epsilon\,(K^o - \overline{K}^o)$$

one has the K_L^o decaying to $\pi\ell\nu$ in a charge asymmetric way,

$$A = \frac{N(\ell^+) - N(\ell^-)}{N(\ell^+) + N(\ell^-)} = \frac{1 - |x|^2}{|1 - x|^2}\, 2\,\mathrm{Re}\,\epsilon$$

where x is the ratio of the $\Delta S = -\Delta Q$ amplitude to the $\Delta S = \Delta Q$ amplitude.

We should keep an open mind and allow for the possibility that x is different for the K_{e3} and $K_{\mu3}$ decay modes and consider the data on the charge asymmetry separately. However, the $K_{\mu3}$ data is sufficiently few that this distinction is not justified and we lump everything together. We emphasize the small effect one is trying to measure -- with $x = 0$, $2\,\mathrm{Re}\,\epsilon = A \sim 2.9 \times 10^{-3}$.

For the $K_{\mu3}$ mode one measurement exists. Curiously, the measurement of the asymmetry in the K_{e3} mode has been attacked more vigorously -- statistically speaking. Three older results and a preliminary result from a new experiment, just being analyzed, are available and shown in Table II.

Again the dispersion in the results is rather large. The weighted mean is

$$A = 2.88 \pm 0.20 \times 10^{-3} \quad \text{internal error}$$
$$= 2.88 \pm 0.27 \times 10^{-3} \quad \text{external error} \quad .$$

This number is to be compared with the predicted asymmetry using as input the value of ϵ determined from η_{+-} and η_{oo}. With x = 0 we have

$$A = 2 \text{ Re } \epsilon = 2.90 \pm 0.17 \times 10^{-3} \quad \text{(predicted)}.$$

The difference between the predicted and the measured value is (0.02 ± 0.35) x 10^{-3}. Turning the question around and asking for the permissable $\Delta S = \Delta Q$ violation consistent with this data, we obtain Re x = .00 ± .06 and an insignificant sensitivity to Im x.

A departure from the $\Delta S = \Delta Q$ rule was first reported at Aix-en-Provence ten years ago -- slightly more than a 2σ effect. In the meantime many experiments have been done with progressively smaller errors but always about 2σ from zero. Weighted averages of all the data available always demonstrated an effect. Now the result from a single high statistics experiment has become available from a CERN-Orsay-Vienna group which shows no violation of the rule. The current results, reported at the recent Amsterdam conference,(31,32) are

$$\text{For } K_{e3} \begin{cases} \text{Re } x = .05^{+.025}_{-.035} \\ \text{Im } x = -\ .01 \pm .02 \end{cases}$$

$$\text{For } K_{\mu 3} \quad \begin{cases} \text{Re } x' = -.09 \pm 0.10 \\ \text{Im } x' = 0.1 \pm 0.15 \end{cases}$$

Values of x permitted by the errors assigned to these results can change the predicted asymmetry for the K_{e3} decay by ~ 20%.

General Remarks

As seen above, on the basis of the present information, ϵ' is small (if not zero) compared to ϵ. Therefore the CP violation is largely in the mass-decay matrix as opposed to the T = 2 decay amplitude ϵ'.

We recall

$$\epsilon = \frac{p - q}{p + q} = \frac{p^2 - q^2}{(p + q)^2} = \frac{(\Gamma_{12} - \Gamma_{21}) + i(M_{12} - M_{21})}{2(i\delta + 1/2)}$$

where all rates and masses are measured in units of Γ_s. With $M_{12} = M_R + i\,M_i = M_{21}^*$ and $\Gamma_{12} = \Gamma_{21}^*$,

$$\epsilon = \frac{i \text{ Im } \Gamma_{12} + M_i}{i\ \delta + 1/2} .$$

Clearly, the measured phase of ϵ requires $M_i \gg \text{Im } \Gamma_{12}$. As was originally pointed out by Wu and Yang in 1964,[21] if one allows for a maximum CP violation in the 3π and $K_{\ell 3}$ channels, one still cannot account from measured rates for all of ϵ -- one needs some M_i. It is of interest to update their observation on the basis of the latest data. The Imag Γ_{12} term contributes to ϵ at right angles to the natural phase, viz., arg $(1/(i\delta + 1/2)) = 43.0^{\circ}$ and, therefore, the measured phase of ϵ provides constraints on the magnitude of Imag Γ_{12}. Independently, from the measured decay rates, the maximum contributions to Imag Γ_{12} can be obtained and these are listed in Table III. The calculation for the $3\pi^0$ channel assumes the same isotopic spin states are involved as for $\pi^+\pi^-\pi^0$ channel.(1) Barring some gross misbehavior of η_{00}, the sum of the right hand column in Table III, taking into account the errors, can contribute only a tiny fraction of $|\epsilon|$ to the CP violation. This is consistent with the conclusion one draws from the measured phase of ϵ, viz., the 1/20 radian error in arg ϵ would permit a contribution of $2/20 \times 10^{-3} = 0.1 \times 10^{-3}$ to Imag Γ_{12}, comparable to the larger components in the table.

We must conclude that the major contribution to the CP violation is from the imaginary parts of the off-diagonal elements of the mass matrix.

Once one puts the effect in the mass matrix it is correspondingly more inaccessible experimentally, since it involves the exploration of the off-the-mass-shell CP violating effects.

Where does the ultimate source of CP violation reside? As we noted in the beginning, if $\eta_{+-} \neq \eta_{00}$, our diagnosis of the source would be simplified. However, since they are not distinctly different we must continue to explore nearly all possibilities. A spectrum of these possibilities was summarized by Wolfenstein(33) a few years ago and we reproduce from his paper a listing of various models for CP violation and their predicted manifestations. This listing is given in Table IV. We have updated the data in the row devoted to experimental results.

A perusal of the table reveals very few models that can be eliminated, especially when it is recognized that the model prediction, $\eta_{+-} \neq \eta_{oo}$, is an exact statement, small inequalities are permitted by the models and, indeed, in many cases are most likely. More specifically, any model of CP-nonconservation which violates the $\Delta I = 1/2$ rule to the same degree it is violated in CP conserving reactions would not lead to a large enough difference between η_{oo} and η_{+-} to be seen in present experiments. One sees the $\Delta I = 5/2$ model definitely eliminated and the e.m. violation put in an uncomfortable but not completely untenable position by the information about the current limit on the electric dipole moment of the neutron. That is all.

The Table emphasizes another important point. Nearly all of the accessory experiments that have been performed to seek other evidences of CP violation are still too insensitive by one, two, and sometimes three orders of magnitude. The experimental physicists have their work well delineated in the future.

Table IV also demonstrates that the superweak model perhaps enjoys an unjustified popularity since there is clearly no more evidence in its favor than there is for many other models.

Strangeness Changing Neutral Currents

The classical test for the existence of strangeness changing neutral currents has been the search for the decay mode $K_L^o \to \mu^+\mu^-$. Until recently the information on this decay mode had come as a by-product from other experiments, most recently those experiments that have been devoted to studying the 2π decay of the K_L^o. Three years ago a group at Berkeley initiated an experiment specifically targeted toward pushing the neutral current limit down to the point where the 2μ decay mode was expected from straightforward, presumably well understood, electromagnetic processes. In the absence of electromagnetic effects one can also have 2μ's from 2nd order weak processes but this is well below the expected electromagnetic threshold. It was always expected that the electromagnetic effects would lead to a $K_L \to 2\mu$ branching ratio of the order of 10^{-8} and this was a targeted number. More precisely, on the basis of the measured $BR(K_L^o \to 2\gamma) = 5.2 \times 10^{-4}$, the <u>lower limit</u> for $K_L^o \to 2\mu$ has been calculated to be $BR(K_L^o \to 2\mu) \gtrsim 6 \times 10^{-9}$.[34] The result of the Berkeley Bevatron[35] experiment was one dubious event from which they compute a $BR(K_L \to 2\mu) = 6.8 \times 10^{-10}$. The probability of getting 1 event (even a good event) or less when you are entitled to at least 10 is

$$\text{Prob} \leq 11\ e^{-10} \cong 10^{-3}/2\ .$$

Since the theoretical estimate is a lower bound a reasonable probability is much less than this. So it is clear we are dealing with an absolutely extraordinary bad run of statistics, or a deceptive theoretical estimate, or some exciting new physics. The experiment has no perceptible faults. It has been meticulously performed. With respect to the theoretical estimate for the EM rate, it should be noted that in the case of eta decay a similar estimate appears to work, i.e.

$$\frac{\Gamma(\eta \to \mu^+\mu^-)}{\Gamma(\eta \to \gamma\gamma)} \geq 1.1 \times 10^{-5} \qquad \text{predicted}^{(36)}$$

$$= 5.9 \pm 2.2 \times 10^{-5} \qquad \text{measured}^{(37)}.$$

In short, there is a problem interpreting this experimental result within the framework of our present knowledge. Christ and Lee[38] and M. K Gaillard[39] have suggested a way out involving CP violation. They invoke K_1^o and K_2^o decay amplitudes to 2μ which destructively interfere. We note that the $\mu^-\mu^+$ system in a ^3P_o state has CP = +1 and in a ^1S_o state has CP = -1. We recall

$$K_L^o = (K^o + \overline{K}^o) + \epsilon(K^o - \overline{K}^o)$$

$$= K_2^o + \epsilon K_1^o .$$

For the amplitudes for K_1^o and K_2^o decay to interfere they must decay to the same state, either ^3P_o or ^1S_o and therefore either the K_2^o or the K_1^o decay must violate CP.

If the K_2^o rate to 2μ's is near the unitarity limit then the CP violating rate for K_1^o and 2μ's would have to be $\sim (\frac{1}{\epsilon})^2$ times as large. The Christ-Lee estimate is

$$BR = \frac{\Gamma(K_S \to 2\mu)}{\Gamma(K_S \to \text{all})} > 5 \times 10^{-7}$$

The current limit on $K_S \rightarrow 2\mu$ comes from Hyams et al.[40] and is within a factor of 10 of addressing the current question.

Their result is

$$\frac{\Gamma(K_S \rightarrow 2\mu)}{\Gamma(K_S \rightarrow \text{all})} \leq 7.3 \times 10^{-6} \text{ 90\% confidence.}$$

Needless to say, these developments have initiated great interest in studying $K_S^o \rightarrow 2\mu$ as well as $K_S^o \rightarrow 2\gamma$. Three different experiments devoted to the latter decay have been reported. Cline et al.,[41] Gaillard et al.,[42] and Nauenberg et al.,[43] each have limits of $\sim 2 \times 10^{-3}$. Combined, the limit becomes $\lesssim 10^{-3}$.

The Weak Equivalence Principle

Ten years ago M. L. Good[44] observed that the neutral K meson system provided a sensitive test of the Equivalence Principle in Relativity. He observed that if the K^o and $\bar{K}^o$ experienced gravitational forces of opposite sign they would be mixed so quickly after the production of a K^o or $\bar{K}^o$, the K_L^o would not exist. He established limits by using the (apparent) absence of K_L^o decay to 2 pions and concluded that the K^o and $\bar{K}^o$ had the same gravitational mass to within about $.7 \times 10^{-7}$ if one were dealing with an isolated earth, about $.5 \times 10^{-8}$ for an isolated solar system, and $\sim 10^{-10}$ if one considered an isolated galaxy. The equal gravitational mass of particle and antiparticle is a manifestation of the so-called weak equivalence principle of general relativity[45] as contrasted to the "strong" equivalence of gravitational and inertial mass.

It is of considerable interest to ask what new limits can be set on the weak equivalence principle using all the new and rather refined data on the neutral K system.[46]

On the surface of an isolated earth, radius R, the gravitational potential energies[47] of the K^o and $\overline{K}^o$ <u>at</u> <u>rest</u> are

$$V_{K^o} = M_K gR\ (1 + \varkappa)$$

and

$$V_{\overline{K}^o} = M_K gR\ (1 - \varkappa)$$

where g is the usual gravitational acceleration and where $\varkappa$, the fractional difference between the particle and antiparticle gravitational mass, parameterizes the violation of the weak equivalence principle.

We note that

$$\frac{V_{K^o}}{M_K c^2} = \frac{gR}{c^2} \cong 7 \times 10^{-10}$$

or

$$V_{K^o} \cong 0.35 \text{ eV} \quad .$$

The potentials appear in the diagonal elements of the mass-decay matrix and lead to a relative amplitude for $K^o_L \to 2\pi$ decay compared to $K^o_S \to 2\pi$ of

$$\Delta = \frac{i\varkappa\, V_{K^o}\, \tau_s}{(i\delta + 1/2)\hbar}$$

where now, since $|\Delta| \ll |\eta_{+-}| = 1.9 \times 10^{-3}$ and $\hbar/\tau_s = 8 \times 10^{-6}$ eV, one can see the enormous sensitivity.

Two effects serve to distinguish the effect of a failure of the weak equivalence principle from a violation of CP. First, Δ is 90^o out of phase with the measured η_{+-} or ϵ. Second, we expect the potential V_{K^o} to transform from the rest system to the moving system with a

$$\gamma^2 = \left(\frac{E_K}{M_K}\right)^2$$

dependence since we are dealing with a spin 2 field.

Correspondingly

$$\Delta = \frac{i\kappa\, V_{K^o}\, \tau_s}{(i\delta + 1/2)\hbar} \left(\frac{E_K}{M_K}\right)^2 = \Delta_o \left(\frac{E_K}{M_K}\right)^2$$

with the branching ratio, BR, proportional to Δ^2. The γ dependence of the BR was tested several years ago with the result[48] BR $\propto E_K^{.03 \pm .08}$ clearly excluding spin 1 and higher fields. Our precise knowledge of the phase is the new element in the picture. Because the phase of Δ is 90^o away from the measured phase, Δ can be, at most, only a small part of η_{+-}.

To set new limits on κ we factor η_{+-} into two parts, one CP violating, which we allow, for these purposes, to have a completely arbitrary phase, and Δ, with its dependence on γ^2. Therefore, we let

$$\eta_{+-} = A\ (\text{CP violating}) + \Delta_o\ (E_K/M_K)^2$$

with

$$\text{BR} \propto |\eta_{+-}|^2 \quad .$$

We have used the phase and branching ratio data given in Table IV, solved for Δ, and obtain

$$\frac{|\Delta_o|}{|A|} = .006^{+.0035}_{-.0044}$$

and arg A = 37° (for $\varkappa$ positive). The new limits for the weak equivalence principle are, accordingly,

$$\varkappa = 1.9^{+1.0}_{-1.4} \times 10^{-10} \qquad \text{earth}$$

$$\varkappa = 1.4^{+\ .8}_{-1.0} \times 10^{-11} \qquad \text{solar system}$$

$$\varkappa \cong 2.8^{+1.6}_{-2.1} \times 10^{-13} \qquad \text{galaxy} \quad ,$$

where the errors are purely statistical and do not reflect, e.g., our ignorance of the precise potential in the galaxy. The best fit for Δ_o, and correspondingly for $\varkappa$, is slightly more than 1 σ from zero. It is certainly consistent with zero and the results above must be treated as limits. The branching ratio and phase information contribute almost equally to the result.

Measurements of the branching ratio and phase at N.A.L. energies will make it possible to extend our knowledge of the weak equivalence principle by 4 to 5 orders of magnitude. It will be highly interesting to see the result.

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Table I

Compendium of $|\eta_{oo}|^2$ Results

$|\eta_{oo}|^2$	Technique	Reference
- 2.0 ± 7.0	S.C.	12
5.3 ± 1.3	S.C.	13
15.2 ± 3.6	S.C.	14
11.8 ± 3.4	S.C.	18
3.7 ± 1.7	HLBC	16
4.3 ± 0.9	Xenon B.C.	15
10.0 ± 4.2	S.C.	17
8.6 ± 2.2	S.C.	20
3.76 ± 0.45	S.C. + Pb Glass	19

Table II

Experimental Results on the $K_{\ell}^{o} \rightarrow \pi^{+} \ell^{\pm} \nu$ Charge Asymmetry

$A_e \times 10^3$	$A_\mu \times 10^3$		Ref.
	4.90 ± 1.6	Dorfan, et al.	26
2.46 ± 0.59		Bennett et al.	27
3.46 ± 0.33		Marx	28
3.6 ± 1.8		Ashford	29
2.48 ± 0.28		Princeton	30

TABLE III

Contributions to Imag Γ_{12} from Various Decay Channels

Channel		Value x 10^3
K_{e3}	2 Imag x (Rate $K_L \rightarrow \pi e \nu$/Rate K_S - total)	.013 ± .026
$K_{\mu 3}$	2 Imag x' (Rate $K_L \rightarrow \pi \mu \nu$/Rate $K_S \rightarrow$ total)	.010 ± .13
$K_{\pi^+\pi^-\pi^0}$	Imag η_{+-0} (Rate $K_L \rightarrow \pi^+\pi^-\pi^0$/Rate $K_S \rightarrow$ total)	.03 ± .04
$K_{3\pi^0}$	Imag η_{000} (Rate $K_L \rightarrow 3\pi^0$/Rate $K_S \rightarrow$ total)	.05 ± .07

To be compared with

ϵ		1.99 ± .07

Table IV

Predictions of Some Models of PC Violation (from Wolfenstein, Ref. 33) and the Current Experimental Situation

Model	$\left\|\frac{\eta_{oo}}{\eta_{+-}}\right\|$	φ_ϵ	$K^o\to 3\pi$ Imag η_{+-o}	$K^{\pm}\to 3\pi$ Δ	β-decay $\varphi(G_A/G_V)$	$K^o\to\pi\ell\nu$ Im x	$\eta\to\pi^+\pi^-\pi^o$ asym.	$K^o\to\gamma+\gamma$ V_a	El of neut. E x (10^6 to 10^7)
Strong $\Delta\vec{I} = 0$	$\simeq 1$	43 ± 1	$\sim 10^{-3}$	$\lesssim 10^{-3}$	$\sim 10^{-3}$	0	$< 10^{-3}$	$< 10^{-2}$	$\sim 10^{-3}$
Strong $\Delta\vec{I} \neq 0$	$\neq 1$	43 ± 1	$\sim 10^{-3}$	$\lesssim 10^{-3}$	$\sim 10^{-3}$	0	10^{-3} to 10^{-1}	$< 10^{-2}$	$\sim 10^{-3}$
Electromagnetic	$\neq 1$	43 ± 1	$\sim 10^{-3}$	$\lesssim 10^{-3}$	$\sim 10^{-3}$	0	10^{-3} to 10^{-1}	large	~ 1
Glashow (D = 0)	$\neq 1$	43 ± 1	$\sim 10^{-3}$	0	10^{-3}	0	0	$< 10^{-2}$	$\sim 10^{-3}$
Glashow (S = 0)	1	35 to 51	.02 to .5	.002 to .05	10^{-2} to 10^{-3}	0	0	$< 10^{-2}$	$\sim 10^{-2}$ to 10^{-3}
$\Delta I = \frac{5}{2}$	$\simeq 2$	a	$\sim 10^{-4}$	$\lesssim 10^{-3}$	0	0	0	$< 10^{-2}$	$< 10^{-6}$
Sachs	1	> 25 < 43	η_{+-}	0	0	$\neq 0$	0	$r\eta_{+-}$ [b]	$< 10^{-12}$
Weak + e.m.	$\neq 1$	43 ± 1	$\sim 10^{-3}$	$\lesssim 10^{-3}$	$\sim 10^{-3}$	0	0	large	~ 1
Okubo	$\neq 1$	43 ± 1	$\sim 10^{-3}$	$\lesssim 10^{-3}$	$\sim 10^{-3}$	0	0	$< 10^{-2}$	$\sim 10^{-3}$
Superweak	1	43	η_{+-}	0	0	0	0	$r\eta_{+-}$ [b]	$< 10^{-8}$
Experiment	1.07±.08	43 ± 3	-.05±.24	(0.4±0.6) x10^{-3} and 1.7±2x10^{-3}	.005	-.01±.02	3±20x10^{-4}		$\lesssim 10^{-1}$ to 10^{-2}
Ref to Exp.			(2)	(53)	(54)	(1)	(55)		(56)

a $|\epsilon| \simeq 0, \varphi_\epsilon$ is undetermined

b $$r = \frac{\gamma_S(\gamma\gamma)}{\gamma_L(\gamma\gamma)} + \frac{\gamma_L(\gamma\gamma)}{\gamma_S(\gamma\gamma)}^{\;1/2}$$

Table V

Data on the η_{+-} as a Function of Momentum

Branching Ratio $\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \text{all charged})$	Momentum (GeV/c)	Ref.
2.0 ± 0.4	1.1	49
1.97 ± 0.16	1.55	48
2.08 ± 0.35	3.14	50
1.99 ± 0.08	4.8	51
3.5 ± 1.4	10.7	52
Phase		
$36.2^\circ \pm 6.1^\circ$	2.6	9
$43.0^\circ \pm 4.0^\circ$	2.5	5
$47.0^\circ \pm 12.0^\circ$	6.5	10 (Bohm, et al.)

Figure Captions

Fig. 1 The distribution of K_{e3} decay events with (b) and without (a) the Cu regenerator as a function of the separation parameter $\Delta_\nu = p_\nu(c.m.) - p_{\nu\perp}$. The diffractively scattered events are clearly evident in the region of negative Δ_ν.

Fig. 2 The charge asymmetry as a function of proper time for various regions of Δ_ν. The best fits, which include the diffractive and incoherent contributions, are shown.

Fig. 3 The history of the measurements of $|\eta_{oo}|^2$.

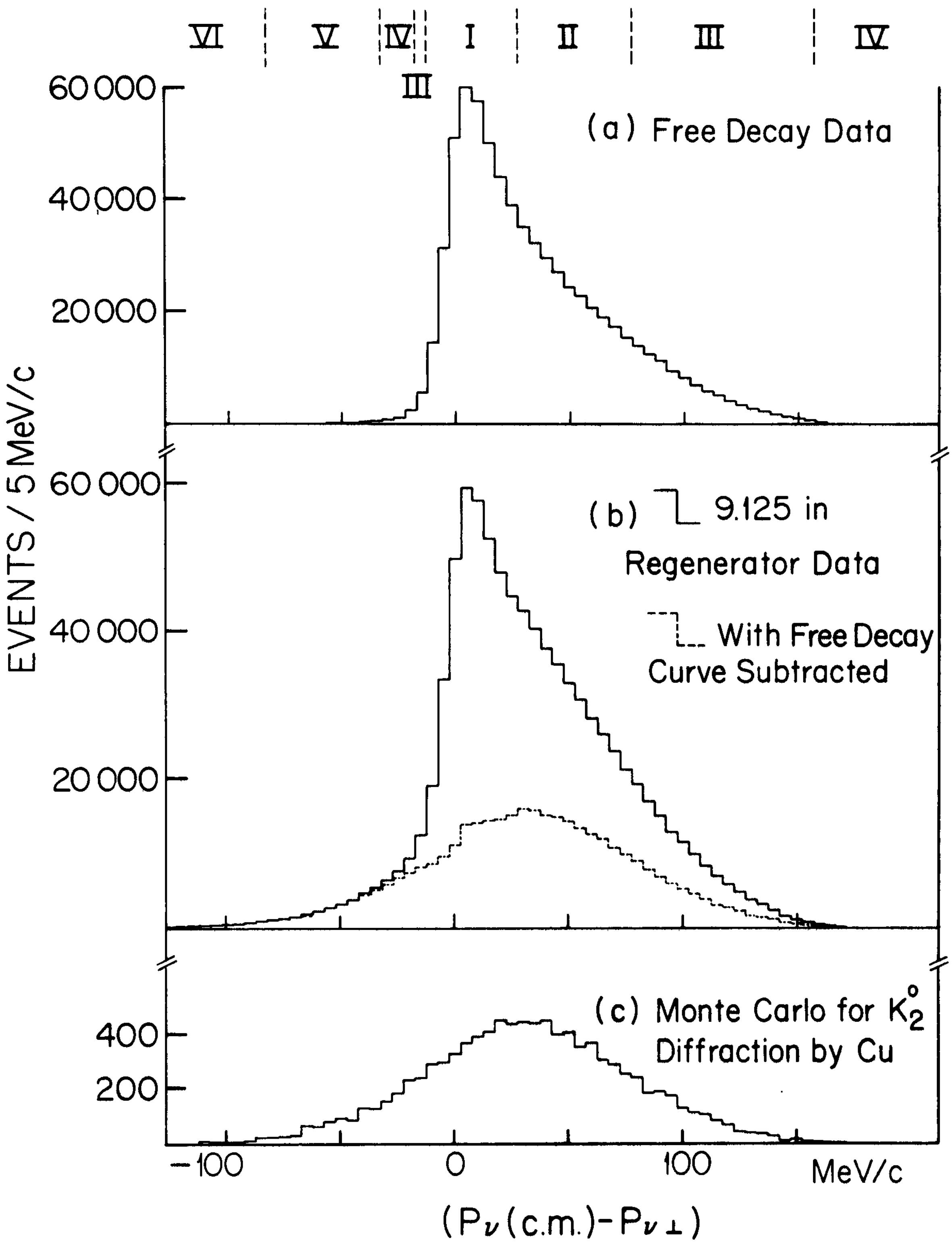
VI
V
IV
III
I
II
III
IV
60 000
40 000
20 000
(a) Free Decay Data
EVENTS / 5 MeV/c
60 000
40 000
20 000
(b) 9.125 in
Regenerator Data
With Free Decay
Curve Subtracted
(c) Monte Carlo for K_2^0
Diffraction by Cu
400
200
−100
0
100
MeV/c
$(P_\nu(c.m.) - P_{\nu\perp})$

Figure 1

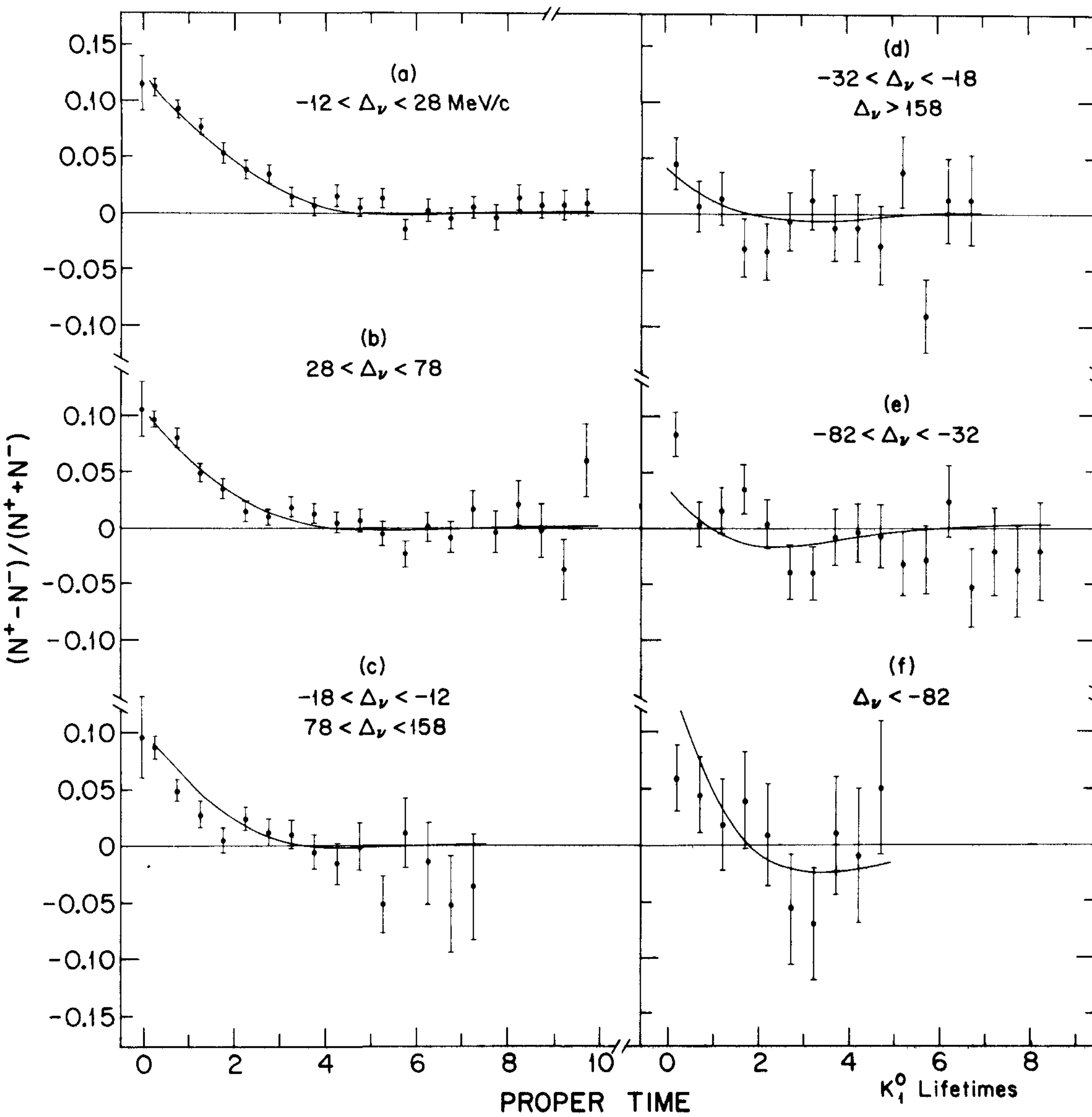
(a)
−12 < Δν < 28 MeV/c
(b)
28 < Δν < 78
(c)
−18 < Δν < −12
78 < Δν < 158
(d)
−32 < Δν < −18
Δν > 158
(e)
−82 < Δν < −32
(f)
Δν < −82
(N+−N−)/(N++N−)
0.15
0.10
0.05
0
−0.05
−0.10
−0.15
0
2
4
6
8
10
PROPER TIME
K10 Lifetimes

Figure 2

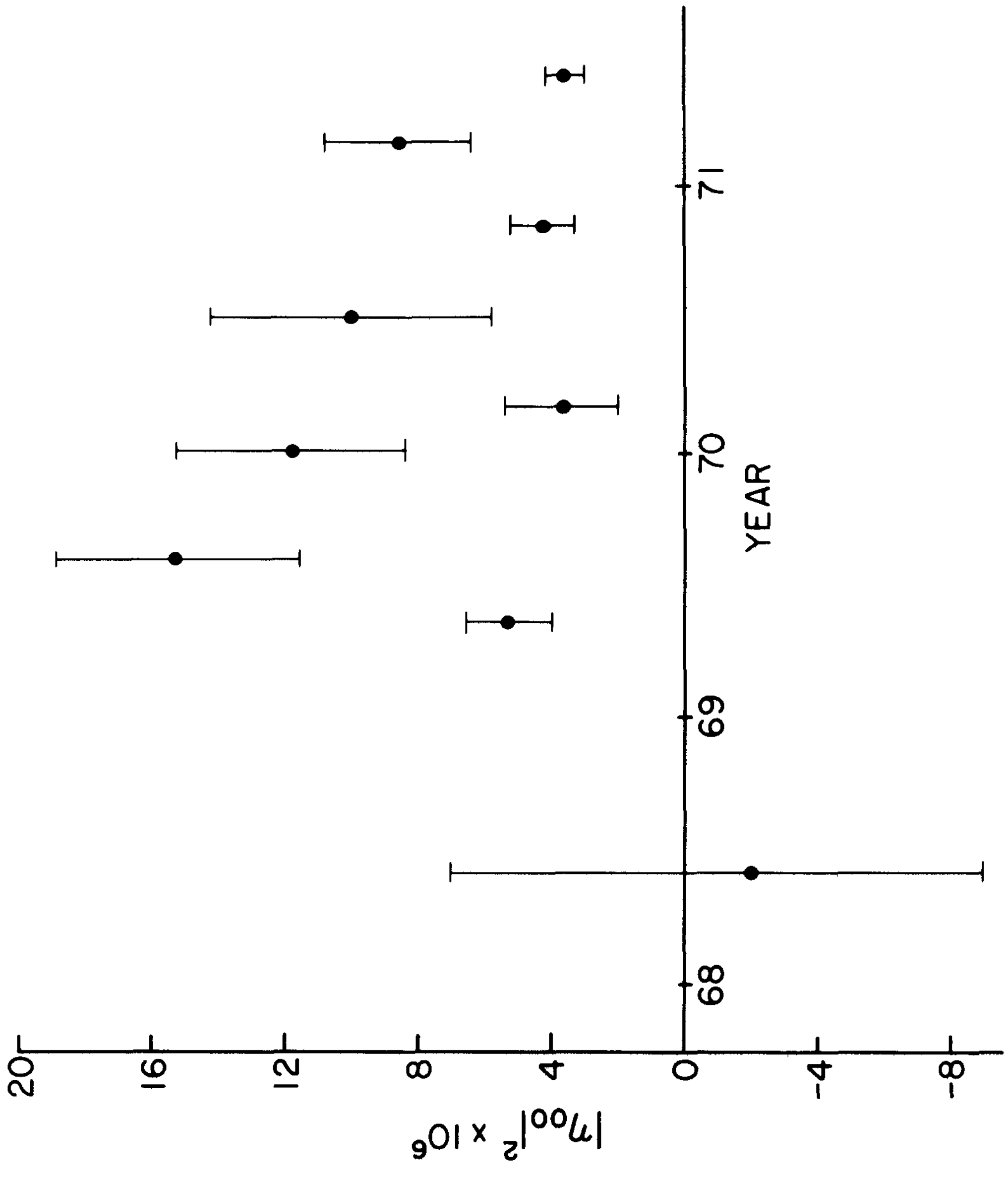

Figure 3