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Measurement of the Total Absorption Coefficient of Long-Lived Neutral K Particles*

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(Received October 16, 1957)

Long-lived neutral K particles have been detected electronically and their total absorption cross section in copper has been measured in good geometry. The observed value of $\sigma=1.12\pm0.25$ barns is compared with the corresponding values for charged-K-particle cross sections.

I. INTRODUCTION

THE existence of the θ_2 component of the neutral K-meson scheme as proposed by Gell-Mann and Pais[1] has been well-established, primarily as the result of the work of Lande *et al.*[2]

We describe here a measurement that records the θ_2 decay process by a direct counting method. The arrangement provides a characteristic signature of the decay event which signals a time coincidence of two particles decaying out of a neutral beam; one of the particles is then followed by a further particle in a time characteristic of the $\mu-e$ decay interval.

The experiment serves the following purposes: (a) to add evidence to that already available concerning the existence of the long-lived θ_2 component; (b) to measure the total-absorption cross section of the θ_2 in good geometry. The cross-section value is then compared with the information existing on charged K particles of positive and negative strangeness.

The analysis of this experiment is not affected by the lack of conservation of parity and of charge-conjugation invariance, and is only slightly influenced by a possible lack of time-reversal invariance in the decay of the neutral-K complex.[3] Even though a small admixture of 2π decays to the long-lived component is possible in principle, both experiment[2] and theory[3] indicate that this admixture is small.

Interpretation of this experiment as a means of demonstrating the existence of a negative-strangeness component in the θ_2 long-lived neutral K meson could be based on comparison of the measured absorption cross section with the corresponding quantities for K^+ mesons. Details of this comparison will be discussed below.

This experiment measures the absorption of θ_2 mesons at a distance (4 ft) from the production target large compared to the θ_1 mean decay distance. If we assume the basic correctness of the Gell-Mann and Pais scheme,[1] then the absorption of the θ_2 component in an absorber of thickness x can be expressed in terms of the following quantities: σ^+, the inverse of the mean absorption length of a particle of positive strangeness; σ^-, the inverse of the mean absorption length of a particle of negative strangeness; μ, the inverse of the decay length of the θ_1 particle; and $\beta=(E_2-E_1)/\mu v\hbar$, where E_2 and E_1 are the total relativistic energies of the θ_2 and θ_1 components, respectively, and v is their velocity. It is of course assumed that the quantities σ^+ and σ^- refer to the absorption geometry of the experimental arrangement. Using an analysis similar to that described by Case,[4] obtained by integrating the differential relations describing the growth and decay of the various components, we obtain for the θ_2 amplitudes as a function of x:

$$\frac{\theta_2(x)}{\theta_2(0)}=\frac{1}{2}\left[\left(1+\frac{1+2i\beta}{[\alpha^2+(1+2i\beta)^2]^{\frac{1}{2}}}\right)\exp(\lambda_1 x)+\left(1-\frac{1+2i\beta}{[\alpha^2+(1+2i\beta)^2]^{\frac{1}{2}}}\right)\exp(\lambda_2 x)\right], \quad (1)$$

where

$$\lambda_1=-\tfrac{1}{2}(\mu+\sigma^++\sigma^-)+\tfrac{1}{2}\mu[\alpha^2+(1+2i\beta)^2]^{\frac{1}{2}},$$
$$\lambda_2=-\tfrac{1}{2}(\mu+\sigma^++\sigma^-)-\tfrac{1}{2}\mu[\alpha^2+(1+2i\beta)^2]^{\frac{1}{2}}, \quad (2)$$

and

$$\alpha=(\sigma^--\sigma^+)/\mu. \quad (3)$$

It is seen that with reasonable parameters the absorption does not differ significantly from a purely exponential absorption; an extremely accurate experiment would be required to demonstrate a deviation from a pure exponential. The reason for this is that in general the quantity α defined by Eq. (3) is small, i.e., the θ_1 decay length is short compared to the difference in absorption length between the components of opposite strangeness. Thus the beam is almost pure θ_2 through the absorber because of the rapid decay of the θ_1 component. In the limit $\alpha\to0$, Eq. (1) gives the pure

* Work performed under the auspices of the U. S. Atomic Energy Commission, and of the joint program of the Atomic Energy Commission and the Office of Naval Research.

[1] M. Gell-Mann and A. Pais, Phys. Rev. 97, 1387 (1955).
[2] Lande, Booth, Impeduglia, Lederman, and Chinowsky, Phys. Rev. 103, 1901 (1956); Lande, Lederman, and Chinowsky, Phys. Rev. 105, 1925 (1957).
[3] Lee, Oehme, and Yang, Phys. Rev. 106, 340 (1957).
[4] K. M. Case, Phys. Rev. 103, 1449 (1956).

Anomalous Regeneration of K_1 -Mesons from K_2 -Mesons

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and

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A beam of 1.0 Bev/c K_2 -mesons passing through liquid hydrogen in a bubble chamber was seen to generate K_1 -mesons with the momentum and direction of the original beam. The intensity of K_1 -production was far greater than that anticipated from conventional mechanisms and the suggestion is made that the K_1 -mesons are produced by coherent regeneration resulting from a new weak long-range interaction between protons and K-mesons.

INTRODUCTION

The fundamental interactions or forces which are now known are commonly divided into four classes; the strong nuclear interactions, the electromagnetic interaction, the weak or beta-decay interaction, and the gravitational interaction. These are simply differentiated by their different magnitudes and different symmetry properties. The assumption that there is a unique, well-defined, largely separate description for each of these classes of forces is attrac[illegible] and the investigation of the axiom for the strong interactions, and for the

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** Now at the University of Birmingham.

⊥ A. P. Sloane Fellow.

#181

PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

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(April 10, 1963)

I. INTRODUCTION

The present proposal was largely stimulated by the recent anomalous results of Adair et al., on the coherent regeneration of K^o_1 mesons. It is the purpose of this experiment to check these results with a precision far transcending that attained in the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K^o_2 \rightarrow \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \rightarrow \mu^+ + \mu^-$. In addition, if time permits, the coherent regeneration of K_1's in dense materials can be observed with good accuracy.

II. EXPERIMENTAL APPARATUS

Fortuitously the equipment of this experiment already exists in operating condition. We propose to use the present 30° neutral beam at the A.G.S. along with the di-pion detector and hydrogen target currently being used by Cronin, et al. at the Cosmotron. We further propose that this experiment be done during the forthcoming μ-p scattering experiment on a parasitic basis.

The di-pion apparatus appears ideal for the experiment. The energy resolution is better than 4 Mev in the m^* or the Q value measurement. The origin of the decay can be located to better than 0.1 inches. The 4 Mev resolution is to be compared with the 20 Mev in the Adair bubble chamber. Indeed it is through the greatly improved resolution (coupled with better statistics) that one can expect to get improved limits on the partial decay rates mentioned above.

III. COUNTING RATES

We have made careful Monte Carlo calculations of the counting rates expected. For example, using the 30° beam with the detector 60-ft. from the A.G.S. target we could expect 0.6 decay events per 10^{11} circulating protons if the K_2 went entirely to two pions. This means that one can set a limit of about one in a thousand for the partial rate of $K_2 \rightarrow 2\pi$ in one hour of operation. The actual limit is set, of course, by the number of three-body K_2 decays that look like two-body decays. We have not as yet made detailed calculations of this. However, it is certain that the excellent resolution of the apparatus will greatly assist in arriving at a much better limit.

If the experiment of Adair, et al. is correct the rate of coherently regenerated K_1's in hydrogen will be approximately 80/hour. This is to be compared with a total of 20 events in the original experiment. The apparatus has enough angular acceptance to detect incoherently produced K_1's with uniform efficiency to beyond 15°. We emphasize the advantage of being able to remove the regenerating material (e.g., hydrogen) from the neutral beam.

IV. POWER REQUIREMENTS

The power requirements for the experiment are extraordinarily modest. We must power one 18-in. x 36-in. magnet for sweeping the beam of charged particles. The two magnets in the di-pion spectrometer are operated in series and use a total of 20 kw.

AGS #181

May 6, 1963

Profs. J. W. Cronin & V. L. Fitch
Department of Physics
Princeton University
Princeton, New Jersey

Dear Jim and Val:

The High Energy Advisory Committee has asked me to inform you that they have approved your experiment to study K_2^0 decays and interactions at the AGS. Your experiment will be scheduled to take place between the two AGS shutdowns presently scheduled for May 13 to May 27 and July 22 to August 19. During the period from May 27 to July 22 the second phase of the μ-p experiment will be run. Your experiment will come in this period and the exact beginning will depend on the logistics and the schedule at the AGS.

The Committee has approved your experiment for approximately 200 hours. Please note that there are severe boundary conditions as to time because of the above-mentioned shutdowns.

Please contact the AGS staff, in particular Mrs. Blewett, at the earliest time possible in order to prepare for this experiment.

May I remind you that guest appointments are necessary for all members of your group who will be working at Brookhaven. Please inform Mrs. Helen Streeter of the Physics Department regarding your requirements. Please note that the appointment of a non-citizen may take as long as two months.

Housing needs should be specified in detail, with inclusive dates. Mrs. M. D'Ambrosio will handle these requests.

Sincerely,

Ronnie

R. Ronald Rau
Secretary
High Energy Advisory Committee

hld

cc: M. Goldhaber
C. E. Falk
G. K. Green
M. H. Blewett
R. H. Phillips

These are the members of the High Energy Advisory Committee who had the perspicacity to approve Experiment #181.

M. Goldhaber, Chairman
M. H. Blewett
G. K. Green
R. H. Phillips
R. R. Rau, Secretary
R. Serber
R. P. Shutt
L. W. Smith
J. Steinberger
G. C. Wick
C. N. Yang
L. C. L. Yuan

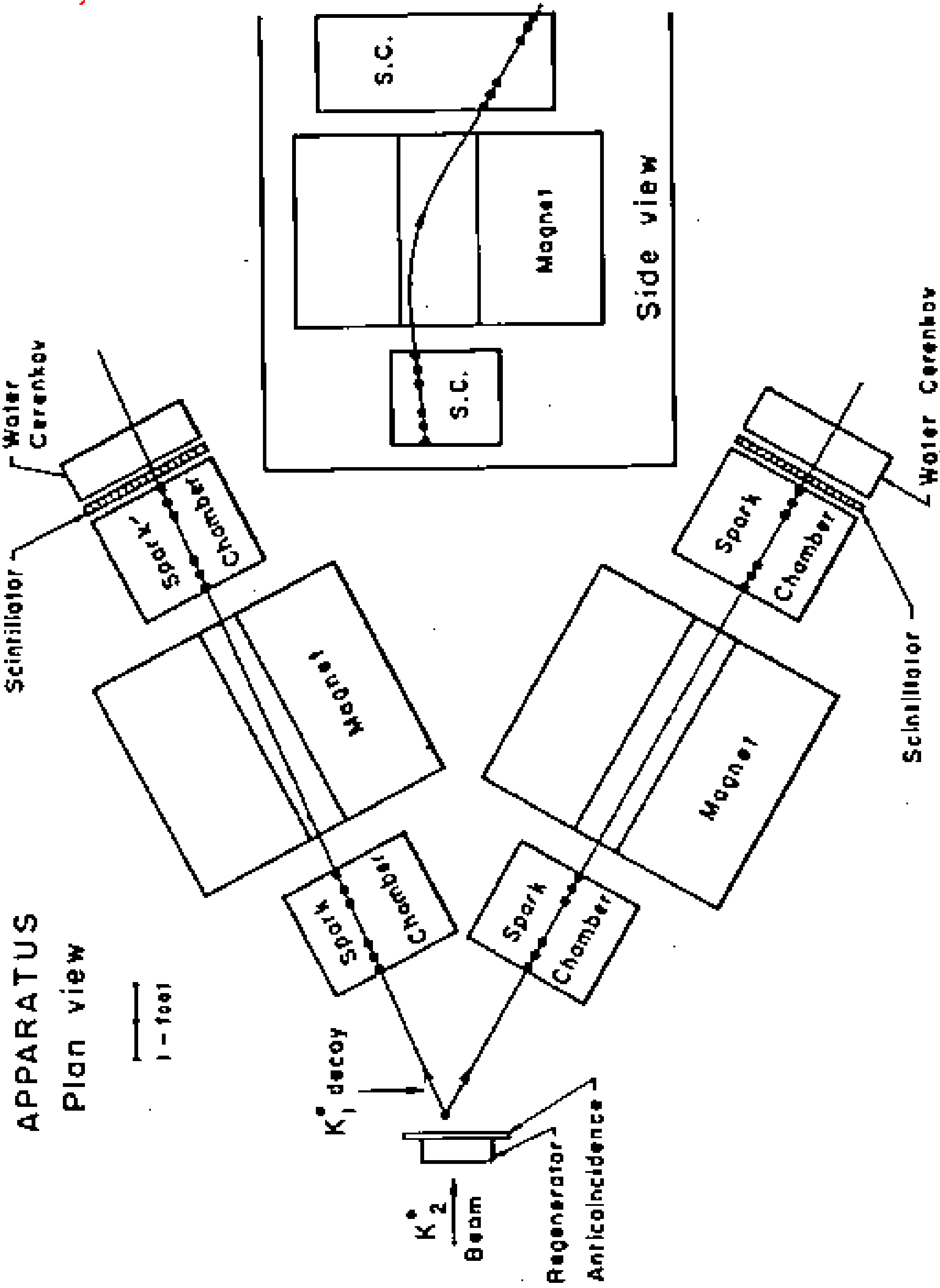
~~CP~~

Christenson, Cronin, Fitch, Turlay

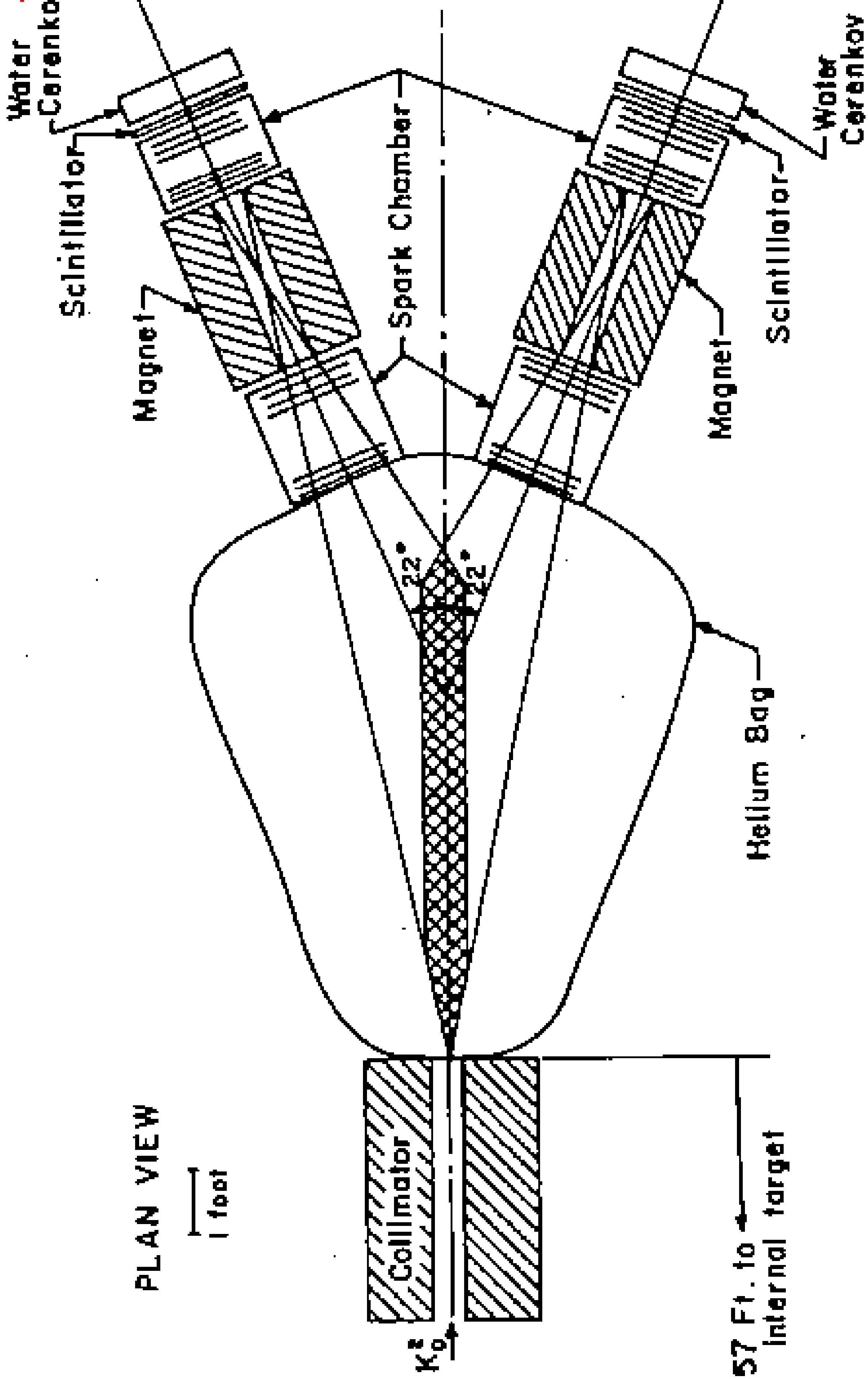
CP Violation in Neutral
K Decay

Carbon Phosphorus Violation in
Neutral Potassium Decay

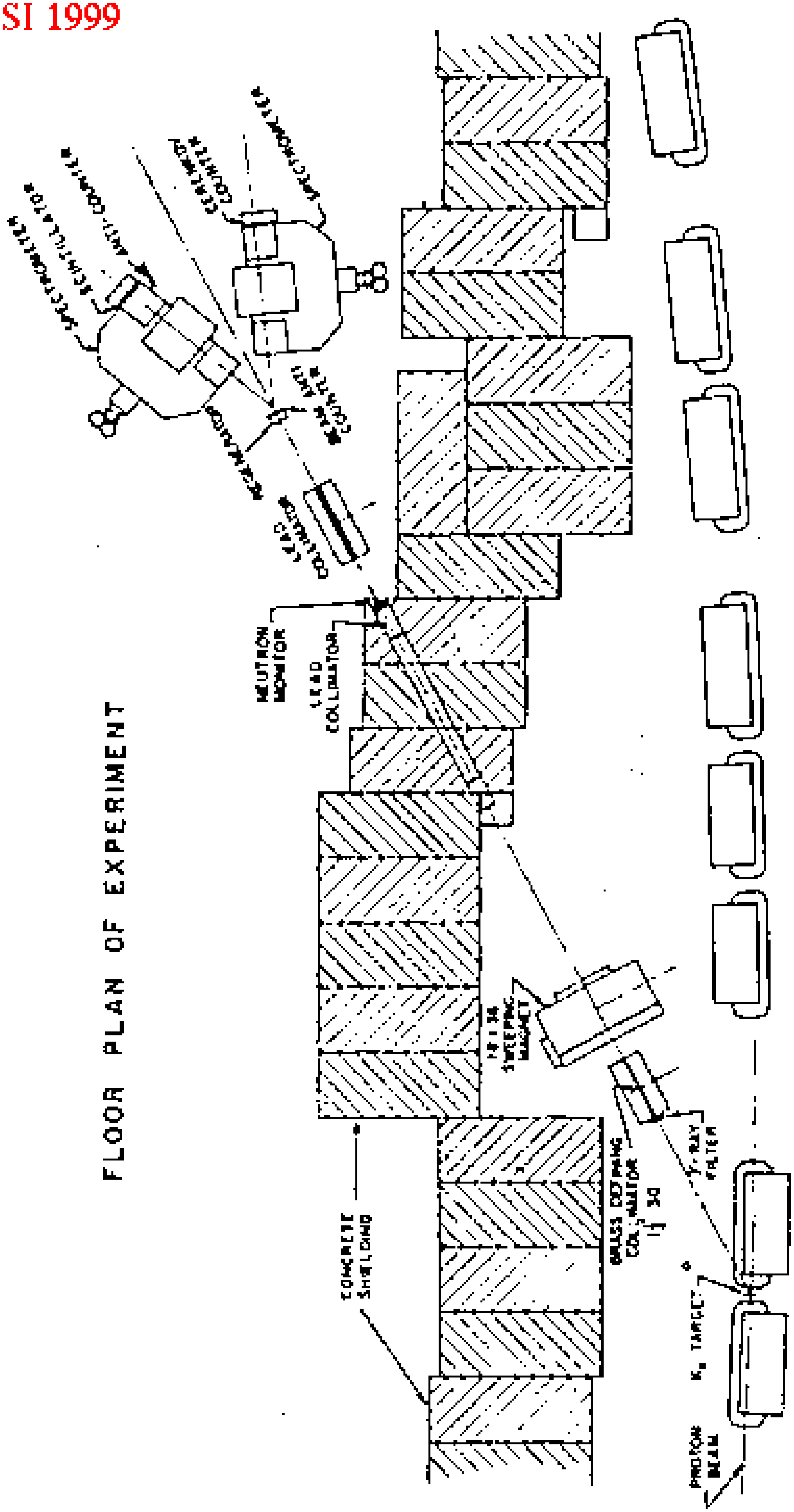
V. Fitch, SSI 1999



V. Fitch, SSI 1999

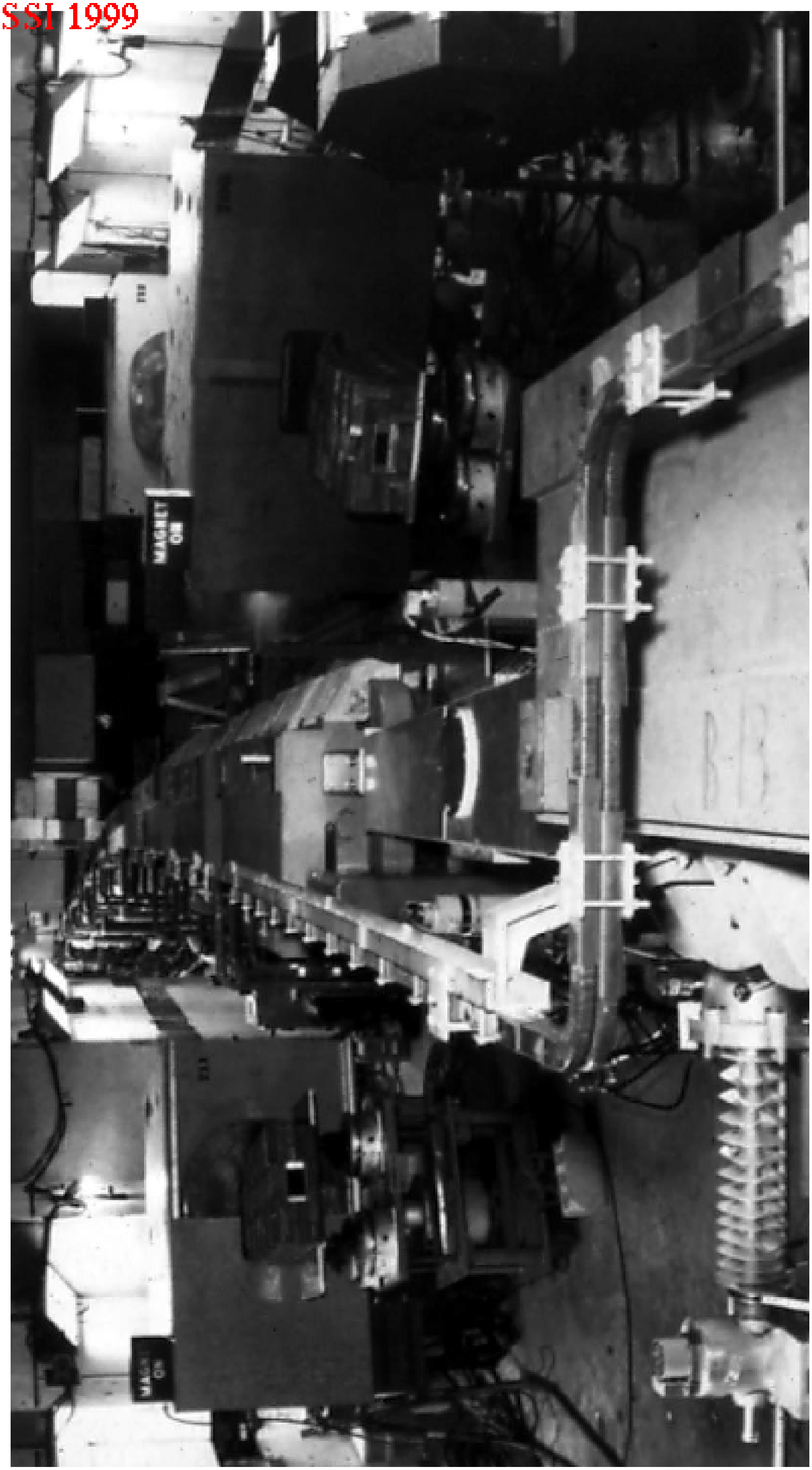


V. Fitch, SSI 1999

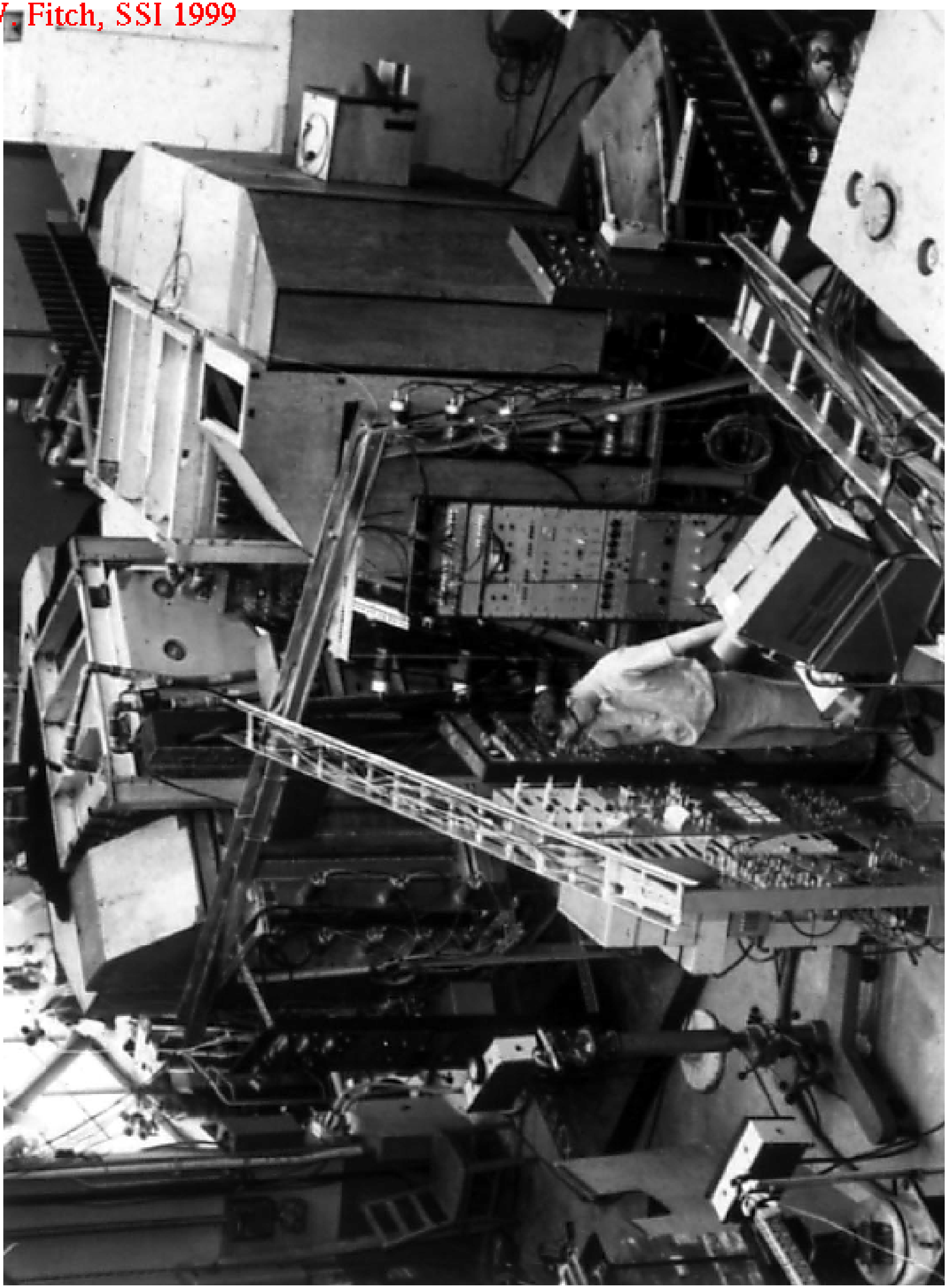


FLOOR PLAN OF EXPERIMENT

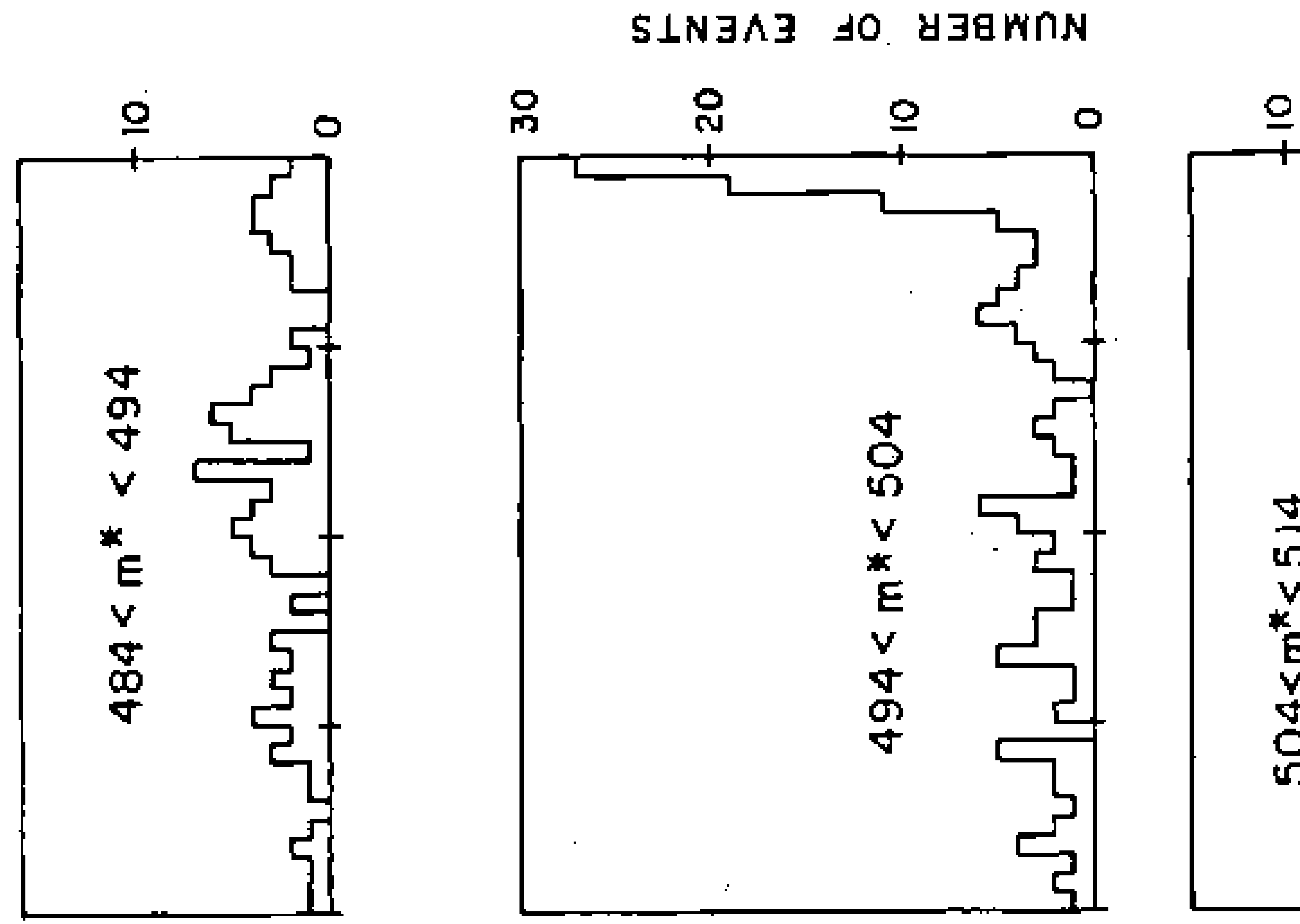
V. Fitch, SSI 1999



V. Fitch, SSI 1999



V. Fitch, SSI 1999



V. Fitch, SSI 1999

V. Fitch, SSI 1999

3 2 N J Pi Pulse. New/Mon NM/N | $3\sigma/3$ N/Pulse $5\sigma/N$ 3/N 2/N

[illegible] revised film lengths than [illegible] - so [illegible] of 6200 pictures - 1550 per 100''

[illegible] 698 461 45.236 .452 | 1.521 21.7 .221 .145 .127

[illegible], 127600, 130150, change film at 131700

[illegible] 11 [illegible] 708 468 41.820 .499 | 1545 20.2 .221 .144 .127

[illegible]

June 20, 1963 — CP INVARIANCE RUN

[illegible] anti and installed Helium bag - bag touches SC. windows and [illegible] H.V. supply - same voltage.

41 .537 .334 — .534 151 1.746

[illegible] not counting - found anti and collector transistors blown in coin[illegible]

[illegible] 317 1382 15.248 .508 | 1.023 21.7 .1816 .1772 .0830

[illegible] meaningless - won't write

[illegible] 100.02 41.62 460 6509 49.192 .492 | .179 .179 .081

[illegible] changing Pb filter - now $2\frac{9}{16}$" ''

219 105 641 6.38 192 997 2588

[illegible] advanced 10 pulses at this point - counters not reset.

17.136 9.997 100.02 41.72 997 5890 49.48 .495 | .185 .181 .0995

18.466 8.862 100.12 41.72 1194 6553 49.823 .495 | .185 .182 .0826

[illegible] 750 [illegible] 30.215 .495 | 16.2 .186 .1815 .0852

From Jules + Jim to Babar + ~~B...~~ Belle

Then + Now

What has changed in 36 years?

(a) Proposal .. 2 pages triple spaced

(b) Magnet Power ... 22 KW

(c) Homemade electronics hybrid vacuum tubes + discrete transistor electronics
H-made NMR to monitor magnetic fld.

(d) Time scale
Proposal April 10 1963
Approved May 6 200 hrs
Data taking May 27 ... July 22
Film measurements completed Nov 1 '63
Paper submitted July 10
published July 27

(e) Lifestyle
No comfortable air-conditioned portacamps - sat out on the floor beside beam-line - hot-dirty-dusty-noisy

Publication July 24 '64

First theoretical paper. Aug. 18 '64

Wu + Yang

"Phenomenological Analysis of the CP-violating Decay of $K_2^0 \to \pi^+\pi^-$"

η_{+-}, η_{00}, ϵ, ϵ', K_L^0, K_S^0.

1 Bernstein, Cabibbo, Lee Aug 18, '64

2 Bell + Perring - Aug 10, '64

3 Tran Truong Aug 19, '64

4 Weinberg 4 Sept. '64

5 Wolfenstein Aug 31 '64

Papers 1, 2, 4 were all devoted to the possibility that the effect was not CP violation but a cosmological effect — a coupling between mass and hypercharge thru a hyperphoton.

Paper 3 suggested that the effect was pure $\Delta I = 3/2$ i.e. totally in ϵ' . .

ington, D. C., meeting of the American Physical Society, 27-30 April 1964. Such resonances should have extremely interesting consequences.

[3]In the well-known octet and decuplet supermultiplet there is no transition which is forbidden by SU(3) and can be used to test symmetry breaking. The forbidden decay of a unitary-singlet vector meson into two pseudoscalars is obscured experimentally by the φ-ω mixing.

[4]The 28-dimensional representation suggested by M. Hogaasen [Nuovo Cimento 32, 1129 (1964)] is ruled out, as it does not appear in the product of three octets.

[5]S. Gasiorowicz, Phys. Rev. 131, 2808 (1963), has considered octet-decuplet resonances in the 35.

[6]S. Okubo, Progr. Theoret. Phys. (Kyoto) 27, 949 (1962).

[7]S. Meshkov, C. A. Levinson, and H. J. Lipkin, Phys. Rev. Letters 10, 100 (1963).

2π DECAY OF THE K_2^0 MESON*

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(Received 10 August 1964)

Evidence has been presented[1] for a small departure from CP invariance in the decay of neutral kaons. Before a more mundane explanation is found, it is amusing to speculate that it might be a local effect due to the dissymetry of the environment, namely the local preponderance of matter over antimatter.

To construct a simple model of such a mechanism, suppose that there is a vector field analogous to the electromagnetic, but coupled to hypercharge rather than charge. The galaxy[2] will give rise to a corresponding potential

$$\varphi \approx gH/R, \tag{1}$$

where g is a coupling constant, R the galactic radius ($\approx 6\times10^{22}$ cm), and H the galactic hypercharge ($\approx 2\times10^{68}$). This potential modifies the free-space Klein-Gordon equation by the substitutions $(i\partial/\partial t) \to (i\partial/\partial t - g\varphi)$ for K_0 and $(i\partial/\partial t) \to (i\partial/\partial t + g\varphi)$ for $\overline{K}_0$. Decoupling the equations one finds that the amplitude for the "wrong" CP state in each eigenstate is

$$|\epsilon| = |(Eg\varphi/m)(\delta m - \tfrac{1}{2}i\delta\Gamma)^{-1}|, \tag{2}$$

where m is the kaon mass, δm the (K_1^0, K_2^0) mass difference, and $\delta\Gamma$ the difference of widths ($\hbar = c = 1$). Using the quoted[1] value $|\epsilon| \approx 2.3\times10^{-3}$, with $(E/m) \approx 2$, and taking[3] $\delta m \approx \delta\Gamma \approx 10^{10}$ sec^{-1}, we find

$$g^2/\hbar c \approx 10^{-49}. \tag{3}$$

This is very weak compared with the gravitational coupling, where M is the proton mass,

$$GM^2/\hbar c \approx 6\times10^{-39}. \tag{4}$$

In fact, (3) is too small by between three and four orders of magnitude to show up in the recent version[4] of the Eötvös experiment. If the quantum of the proposed field did not have zero mass,[5] the potential would have a finite range. If this were less than the radius of the galaxy, larger values of g^2 would be required, and the Eötvös experiment limits the extent to which this would be acceptable.[6]

Clearly this theory[7,8] has a very slender basis. However, it suggests a refinement of the experiment. Our field provides not only a weak local violation of CP invariance, but also of Lorentz invariance. Thus from (2) the branching ratio for anomalous decay varies with the square of the particle energy.

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

†On leave of absence from CERN, Geneva, Switzerland.

‡On leave of absence from Atomic Energy Research Establishment, Harwell, England.

[1]J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters 13, 138 (1964).

[2]In fact, it might be necessary to identify the local preponderance of matter with a still larger unit than the galaxy; see reference 4.

[3]See, for example, the report of W. F. Fry, in Proceedings of the International Conference on the Fundamental Aspects of Weak Interactions (Brookhaven National Laboratory, Upton, New York, 1963).

[4]R. H. Dicke, Phys. Rev. 126, 1580 (1962).

[5]There is a technical difficulty with vector particles of zero bare mass in quantum field theory when the source (hypercharge in this case) is not accurately conserved. See G. Feinberg, to be published.

[6]For example, if the sun is the dominant object within range, with hypercharge about 1.2×10^{57} at a distance of 1.5×10^{13} cm, (3) is replaced by

$$g^2/\hbar c \approx 5\times10^{-48}, \tag{5}$$

which is still two orders of magnitude beyond the limit

for his participation and valuable contribution to the early stages of this experiment.

*Research supported in part by the U. S. Office of Naval Research.

[1]B. M. Chasan, G. Cocconi, V. T. Cocconi, R. M. Schectman, and D. H. White, Phys. Rev. 119, 811 (1960).

[2]R. Hagedorn, Relativistic Kinematics (W. A. Benjamin, Inc., New York, 1963), p. 114, Eqs. 7-58.

[3]D. McLeod, S. Richert, and A. Silverman, Phys. Rev. Letters 7, 383 (1961). The present data are in substantial agreement with the data of this reference.

[4]R. E. Cutkosky and F. Zachariasen, Phys. Rev. 103, 1108 (1956).

[5]Under the assumption that the one-pion exchange dominates process (2), S. M. Berman and S. D. Drell [Phys. Rev. 133, B791 (1964)] inferred a decay width $\Gamma(\rho^0 \to \pi^0 + \gamma) \approx 0.5$ MeV using the data of reference 3. The present data suggest a much smaller value although the decrease we observe in the forward direction could be the result of interference with the 3,3 isobar since for those data $M_{p\pi}$ was near the resonance energy.

[6]J. B. Bronzan and F. E. Low, Phys. Rev. Letters 12, 522 (1964).

DO HYPERPHOTONS EXIST? *

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(Received 4 September 1964)

The existence of the photon naturally suggests that there may also exist other "gauge" particles, coupled to other conserved currents.[1,2] This remained purely a speculation, until the recent appearance of experimental results[3] which seem to indicate a CP-violating $K_2^0 \to 2\pi$ decay. Independent Letters by Bell and Perring[4] and by Bernstein, Cabibbo, and Lee[5] have pointed out that the effect observed can also be interpreted as the regeneration of K_1^0 by a new long-range interaction between the K meson and our galaxy, which would have to act with opposite sign on the K^0 and $\bar{K}^0$ components. Both Letters therefore suggest the existence of spin-one "hyperphotons" coupled to hypercharge (Y), or to Y plus some linear combination of Q and N. The purpose of this note is to argue on empirical grounds against the existence of such hyperphotons, and to indicate where to find them if they do exist.

The hypercharge current is not precisely conserved, so the hyperphoton must[6] have a small but finite mass m. But in all other respects it may be presumed to behave qualitatively like an ordinary photon. We can therefore calculate the matrix element for K^0 decay into two pions and a soft hyperphoton, of momentum q^μ [with $q^0 = \omega \equiv (|\vec{q}|^2 + m^2)^{1/2}$] and polarization ϵ^μ, as[7]

$$M(q,\epsilon) = \frac{fM}{(2\pi)^{3/2}(2\omega)^{1/2}} \frac{2P_K \cdot \epsilon}{(P_K - q)^2 + m_K^2}, \qquad (1)$$

where f is the coupling constant of K^0 to the soft hyperphoton, and M is the matrix element for $K^0 \to 2\pi$. The branching ratio for emission of hyperphotons of energy $\leq E$ in K^0 decay at rest is then

$$\frac{K^0 \to 2\pi + \text{“}\gamma\text{”}}{K^0 \to 2\pi} = \frac{f^2}{4\pi^2 m^2} \int_m^E \frac{(\omega^2 - m^2)^{3/2}}{(\omega - m^2/2m_K)^2} d\omega. \qquad (2)$$

This formula is exact for sufficiently small E and m (say, $\ll 100$ MeV) because then the matrix element is completely dominated by the pole term (1).[7] If we take E of order 100 MeV, and assume (quite safely) that $m \ll E$, then (2) becomes simply

$$\frac{K^0 \to 2\pi + \text{“}\gamma\text{”}}{K^0 \to 2\pi} \cong \frac{f^2 E^2}{8\pi^2 m^2}. \qquad (3)$$

The important point is that (3) depends only upon the ratio f^2/m^2, so a very weak coupling can still give a large branching ratio if m is sufficiently small. This circumstance can be traced back to the longitudinal term $q_\mu q_\nu/m^2$ in the polarization sum, which contributes here because K decay violates hypercharge conservation. Similar conclusions would hold for any $\Delta S \neq 0$ decay process.

How large is f^2/m^2? The apparent $K_2^0 \to 2\pi$ decay rate can be explained by regeneration of K_1^0 if the K^0 and $\bar{K}^0$ are split by the hyperphoton field by an amount $V \cong 10^{-8}$ eV. If hyperphotons interact purely with hypercharge, then

$$V = f^2 \int d^3 r\, n(\vec{r}) e^{-mr}/4\pi r, \qquad (4)$$

where $n(\vec{r})$ is the nucleon number density at position $\vec{r}$ (with K meson at $\vec{r} = 0$). Hence f^2/m^2 must take the value

$$f^2/m^2 = V/\langle n \rangle, \qquad (5)$$

butions are anisotropic, and in particular that of the nucleons is strongly peaked in the forward-backward directions. Similar angular distributions are found for the baryons in the three-body reactions $pp \to YNK$.

The main conclusions from this experiment are: The dominant process of Λ production is associated with $Y_1^*(1385)$ formation, i.e., Λ is mainly produced by the reaction $pp \to Y_1^*NK \to \Lambda\pi NK$. Other possible modes of Λ production like direct production or as a decay product from nucleonic resonances $N^* \to YK$ are small or unimportant in $pp \to YNK\pi$ at 5.52 GeV/c.

In the present work it is difficult to detect the formation of $Y_0^*(1405)$ resonance via the neutral (i.e., $\Sigma^0\pi^0$) decay mode. The only type of events identified as Σ^0 events are those in which there are no invisible neutral particles. The number of Σ^0 events thus identified is small and in agreement with a minor contribution of Σ^0 production through nonresonating states.

It seems that in events of the type $pp \to \Sigma^0(\Lambda)NK$, where either the Σ^0 or the Λ does not belong to a Y_1^*, the N-π pair is associated with the formation of the $N_{3/2}^*(1235)$ resonance.

The lack of direct evidence for the K^* resonance formation and the small cross section for K-$\bar{K}$ production show that the formation of mesonic resonances in the pp reaction at 5.52 GeV/c is unimportant.

We would like to express our gratitude to CERN and to the hydrogen bubble chamber crew for enabling us to have the p-p exposure, and to the CERN programming group for help in the adaptation of CERN programs to our computer.

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†Accepted without review under policy announced in Editorial of 20 July 1964 [Phys. Rev. Letters 13, 79 (1964)].

*Also from the Israel Atomic Energy Commission Soreq Research Establishment, Yavne, Israel.

[1]A similar experiment was carried out at 2.85 GeV by R. I. Louttit et al., Phys. Rev. 123, 1465 (1961).

[2]For the evaluation of the total cross section and beam contamination, see B. Haber, M.S. thesis, The Weizmann Institute of Science, Rehovoth, Israel, 1964 (unpublished).

[3]This is in good agreement with the value of 41.6 ±0.6 mb at 5.83 GeV/c by A. N. Didden et al., Phys. Rev. Letters 9, 32 (1964).

[4]However, the large amount of $Y_1^*(1385)$ formation (see further in the text) supports the identification of the Λ^0 events in the experiment.

[5]C. Robinson, M.S. thesis, The Weizmann Institute of Science, Rehovoth, Israel, 1964 (unpublished); and private communication. The calculations follow E. Ferrari [Phys. Rev. 120, 988 (1960)] and E. Ferrari and F. Selleri [Nuovo Cimento, Suppl. 24, 453 (1962)], extended to 5.5 GeV/c, and using recent data on πN and KN interactions.

POSSIBILITY OF CP VIOLATION IN $\Delta I = \frac{1}{2}$ DECAY OF THE K^0 MESON*

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(Received 19 August 1964)

The existence of the decay mode $K_2^0 \to \pi^+ + \pi^-$ has recently been reported by Christenson, Cronin, Fitch, and Turlay.[1] This establishes the violation of CP invariance. The branching ratio of $K_2^0 \to \pi^+ + \pi^-$ relative to $K_1^0 \to \pi^+ + \pi^-$ is 2.6 $\times 10^{-6}$. In view of this small branching ratio Sachs[2] proposes that this small effect may be an indirect consequence of the maximum violation of CP in the leptonic decay of the K^0 meson. Interesting consequences of this assumption can be readily checked by experiments as discussed by Sachs.

In this note we take a somewhat different viewpoint. We assume that in the (strangeness-changing) decay of the K meson which obeys the $\Delta I = \frac{1}{2}$ rule, CP is conserved, while in the decay which violates this rule CP is violated. Our motivation is inspired by the fact that there is evidently a connection between the strength of interactions and their symmetry property. The presence of the $\Delta I = \frac{3}{2}$ amplitude, as evidenced by the decay of $K^+ \to \pi^+ + \pi^0$, is at least one order of magnitude smaller than that which obeys the $\Delta I = \frac{1}{2}$ rule.[3] Admittedly, our assumption is quite speculative; however, if checked experimentally it might provide some insight to the weak decay mechanism. We have implicitly assumed that the existence of the decay mode $K^+ \to \pi^+ + \pi^0$ is not a consequence of electromagnetic violation of a strict $\Delta I = \frac{1}{2}$ weak interaction. Schwinger[4] has recently constructed a model for the decay of $K^+ \to \pi^+ + \pi^0$ without invoking electromagnetic effect, and pointed out the difficulty in a model with strict $\Delta I = \frac{1}{2}$ rule. The recent experiment on $K^+ \to \pi^+ + \pi^0 + \gamma$ by Cline and Fry[5] indicates that the rate and charged-pion spectrum are quite

FURTHER TESTS OF THE VIOLATION OF CP WITH NEUTRAL K MESONS

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The recent discovery [1] of the violation of CP invariance in the decay $K_L \to \pi^+ + \pi^-$ has stimulated a large number of proposals for the specific mechanism of CP violation. In view of this and of the possibility that the CP violation may be everywhere small, the empirical problem of verifying the many predictions appears very complex. In this letter we intend to consider the possibility of determining the additional parameters in the *total* mass matrix, irrespective of any specific assumptions about the mechanism. Three experiments are proposed, which if successful, would considerably clarify the problem of determining the origin of the CP violations.

The analysis is based on the phenomenological description of neutral kaons [2-4], using a complex mass matrix $\Lambda = M - \frac{1}{2}i\Gamma$. If CP were valid, then, in a suitable representation, Λ would be symmetric both along and across the diagonal, and would therefore have four real parameters. These parameters can be defined by the two complex eigenvalues λ_1 and λ_2, corresponding to the eigenvectors $|K_1\rangle = \frac{1}{2}\sqrt{2}(|K\rangle + |\bar{K}\rangle)$ and $|K_2\rangle = \frac{1}{2}\sqrt{2}(|K\rangle - |\bar{K}\rangle)$. In this representation T implies symmetry across the diagonal and TCP implies symmetry along the diagonal. The CP violation can be described by the two additional complex parameters r and ρ where

$$r = \sqrt{\Lambda_{21}/\Lambda_{12}}\,, \qquad \rho = \eta + \sqrt{1+\eta^2}\,,$$
$$\eta = (\Lambda_{22} - \Lambda_{11})/2\sqrt{\Lambda_{12}\Lambda_{21}}\,,$$

defined so that $r \neq 1$ violates T invariance and $\rho \neq 1$ violates TCP invariance. The eigenvectors corresponding to the eigenvalues $\lambda_{S,L} = m_{S,L} - \frac{1}{2}i\gamma_{S,L}$ become

$$|K_S\rangle = \tfrac{1}{2}\sqrt{2}(|K\rangle + \rho r|\bar{K}\rangle), \quad |K_L\rangle = \tfrac{1}{2}\sqrt{2}(\rho|K\rangle - r|\bar{K}\rangle).$$

These states, together with their "inverse" states (*not* the ordinary Hermitian adjoints)

$$\langle\tilde{K}_S| = (\langle K|r + \langle\bar{K}|\rho)\sqrt{2}/r(1+\rho^2)\,,$$
$$\langle\tilde{K}_L| = (\langle K|\rho r - \langle\bar{K}|)\sqrt{2}/r(1+\rho^2)$$

form a complete orthonormal set. The problem of measuring the widths γ_S and γ_L and the mass difference $\Delta m = m_S - m_L$ has been thoroughly discussed. The problem which we address is that of measuring $Z = 1-r$ and $\zeta = 1-\rho$; that is, of testing T and TCP, and of measuring the magnitude and phase of the CP admixture. (See ref. 3 for earlier discussion of this problem). Neither Z nor ζ is known at present, since the only experimental evidence for CP violation is a measurement of $|\langle 2\pi|H_W|K_L\rangle|^2$, which involves the decay amplitudes as well as Z and ζ.

We propose three experiments to determine Z and ζ. The first is simply a measurement of the total intensity of a neutral kaon beam versus the distance from the production vertex of a K meson. As is well known, the intensity of K and $\bar{K}$ undergo damped oscillation. It was pointed out in ref. 2 that if CP is violated the total intensity can also have a small oscillatory term, arising from the non-unitary character of the relation between $|K\rangle$, $|\bar{K}\rangle$ and $|K_S\rangle$, $|K_L\rangle$. We wish only to add the remark that the *phase* of this oscillatory term is fixed by T or TCP invariance. We find for the total intensity versus proper time

$$A(\tau) = \tfrac{1}{2}\{\exp(-\gamma_S\tau)[1-\mathrm{Re}(Z-\zeta)] + 2\exp[-\tfrac{1}{2}(\gamma_S+\gamma_L)\tau] \times$$
$$[\mathrm{Re}\,Z\cos\Delta m\tau + \mathrm{Im}\,\zeta\sin\Delta m\tau] +$$
$$+ \exp(-\gamma_L\tau)[1-\mathrm{Re}(Z+\zeta)]\}$$

where only first order terms in Z and ζ are retained. We see that T implies an oscillation $\sim \sin(\Delta m\tau)$, whereas TCP implies an oscillation $\sim \cos(\Delta m\tau)$. We also note that the absence of an oscillatory term does not imply invariance

Violation of CP-Invariance and the Possibility of Very Weak Interactions

Phys. Rev. Letters

~~32~~

13 117-119 (1964)

Subsequent experiments were:

1) Demonstration of interference between CP violating + coherently regenerated amplitudes

2) Energy dependence of $|\eta_{+-}|^2 \sim E^{2J}$

3) Measurement of η_{00}

4) Phase of η_{+-}

5) Vacuum Interference between $K_S \to \pi^+\pi^-$ and $K_L \to \pi^+\pi^-$

4) Measurement of the charge asymmetry
$K_L^0 \to e^+\pi^-\nu / K_L^0 \to e^-\pi^+\nu$
$K_L^0 \to \mu^+\pi^-\nu / K_L^0 \to \mu^-\pi^+\nu$

5) Long struggle to measure ϵ'/ϵ

two measurements give positive number
"very soft" theoretical number also pos.

TABLE 14

ϕ_{+-}

Group	P_K (GeV/c)	Regenerator	$\phi_{+-} - \phi_f$	ϕ_f	ϕ_{+-}	Ref.
Princeton	1.55	Be	45° ± 35°	0° ± 15° f_{21}, σ_{tot} Opt.mod.	45° ± 40°	a
CERN	4.8	C	90° ± 6°	-20° ± 20° f_{21}, σ_{tot}	70° ± 21°	b
* CERN-Columbia	2.7	Cu	80.5° ± 10.3°			c
Illinois	1.1	Cu	67° ± 20°	-42° ± 22° Opt.mod.	25° ± 35°	d
Yale-BNL	5	H_2	120° ± 45°	-90°± ? Disp.rel.	30° ± 45°	e
* CERN	7	Vacuum			46° ± 15°	f
Columbia	2.5	Cu		-28.8° ± 4.7°	51.2° ± 11° combined with (c)	g
CERN	3.4	Cu	98° ± 10°		68° ± 7.5° combined with (g)	h

a) V. Fitch et al., Phys. Rev. Letters 15, 73 (1965); Phys. Rev. 164, 1711 (1967).

b) M. Bott-Bodenhausen et al., Phys. Letters 23, 277 (1966), and Phys. Letters 24 B, 438 (1967).

c) C. Alff-Steinberger et al., Phys. Letters 21, 595 (1966).

d) R.E. Mischke et al., Phys. Rev. Letters 18, 138 (1966).

e) A. Firestone et al., Phys. Rev. Letters 16, 556 (1966), and Phys. Rev. Letters 17, 116 (1966).

f) A. Böhm et al., Phys. Letters 27 B, 321 (1968).

g) S. Bennett et al., Phys. Letters 27 B, 239 (1968).

h) V. Bisi et al., abstract 590.

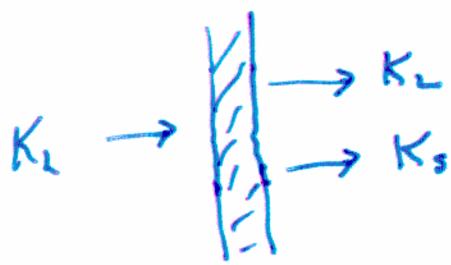
Group	P_K (GeV/c)	$K_L \to 2\pi^0$ normalization	$\lvert\eta_{00}\rvert^2 \times 10^6$	$\lvert\eta_{00}\rvert \times 10^3$	Remarks	Ref.
CERN-RHEL Aachen I	1.5 - 2.75	Regenerated K_S^0	$18.5 {}^{+10.5}_{-6.5}$	$4.3 {}^{+1.1}_{-0.8}$	Superseded by II.	a
Princeton I	0.25 ± 0.10	$3\pi^0$	24 ± 5	4.9 ± 0.5	Withdrawn	b
Princeton	∿ 0.73	Regenerated K_S^0	-2 ± 7	< 3.0	90% confidence level	c
Berkeley-Hawaii	0.53 ± 0.05	$3\pi^0$	13.0 ± 3.0	3.6 ± 0.4		d
CERN-RHEL Aachen II	1.5 - 2.75	Regenerated K_S^0	13 ± 4	3.6 ± 0.6		e
CERN Ec.Pol. Orsay	0.4 - 2.0	$3\pi^0$	4.8 ± 1.8	2.2 ± 0.4		f
Princeton II	0.25 ± 0.10	$3\pi^0$	5.1 ± 1.2	2.3 ± 0.3		g

a) J.M. Gaillard et al., Phys. Rev. Letters 18, 20 (1967).
b) J. Cronin et al., Phys. Rev. Letters 18, 25 (1967).
c) D. Bartlett et al., Phys. Rev. Letters 21, 558 (1968).
d) R.J. Cence et al., paper 476.
e) J.M. Gaillard et al., paper 139.
f) I.A. Budagov et al., paper 377.
g) M. Banner et al., paper 910.

$$m(K_L) - m(K_S) = \Delta m = 0.5301 \pm .0014 \times 10^{1}$$

$$\equiv 1.25 \times 10^{-6}\ \text{eV}.$$

$$\frac{\Delta m}{m_K} = 2.5 \times 10^{-17} \pm 2.8 \times 10^{-21}$$



Interference term

regen $$2|\rho||\eta_{+-}|e^{-\frac{\Gamma_S t}{2}} \cos(-\Delta m t + \phi_\rho - \phi_{+-})$$

from K^0 prod $$2|\eta_{+-}|e^{-\Gamma_S t/2} \cos(-\Delta m t - \phi_{+-})$$

In PL 40B 141 (1972)

$$\frac{\eta_{00}}{\eta_{+-}} = 1.0 \pm 0.06$$

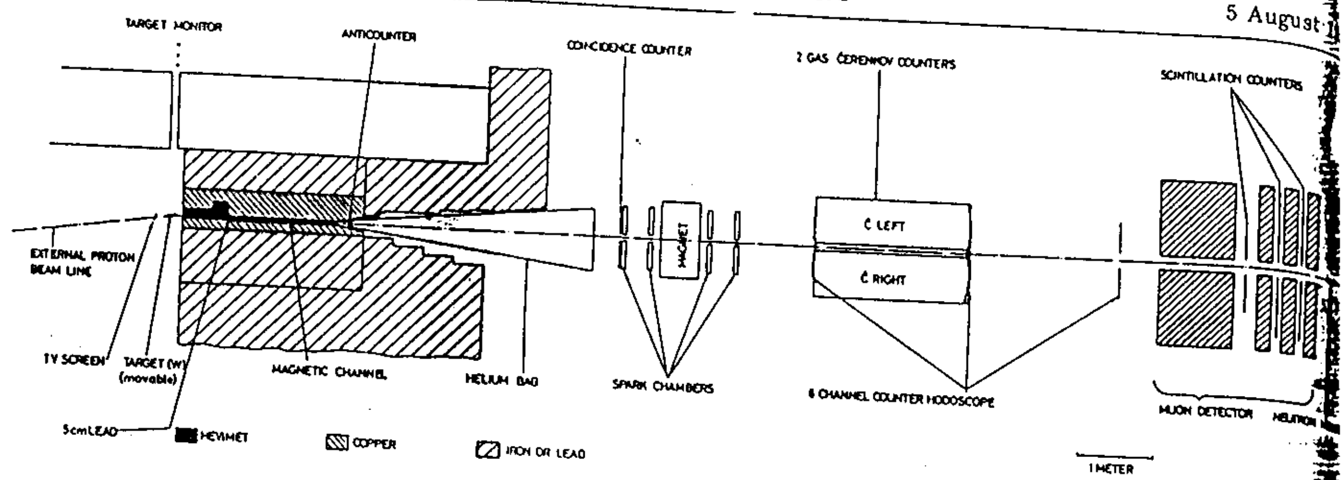
$$Re\,\frac{\epsilon'}{\epsilon} = 0 \pm 0.01$$

$$(0 \pm 100) \times 10^{-4}$$

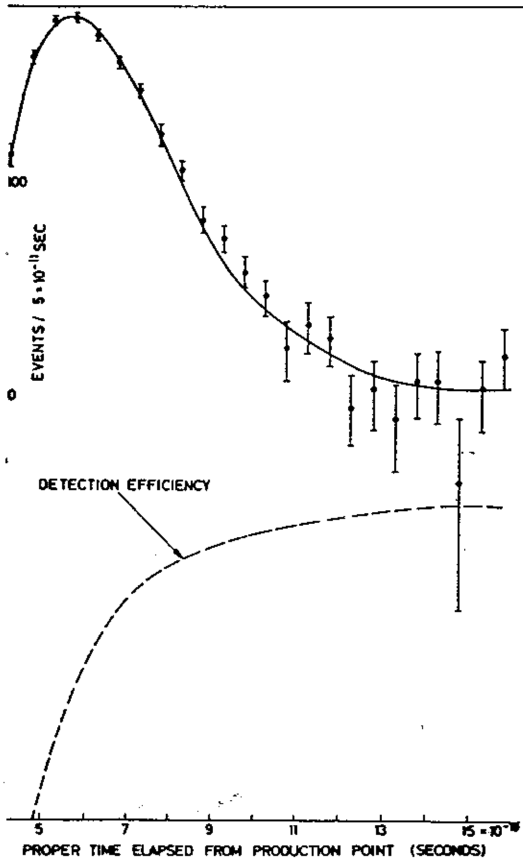
And in PL 43B 529 (1973)

$$\varphi_{00} - \varphi_{+-} = 7.6 \pm 18^{\circ}$$

Volume 27B. number 5 (1968). PHYSICS LETTERS 5 August



V. Fitch, SSI 1999



g. 4. Experimental data and best fit for proper de-y-time distributions of $K \to 2\pi$ events. The time de-ndence of the detection efficiency calculated by a onte Carlo method is also shown (dashed line).

$$\varphi_{+-} = +(46 \pm 15)^\circ \text{ sign } (\Delta m) .$$

e main single contribution to the quoted error is, as pected, due to the indetermination in the mass dif-rence Δm. For different values of Δm the result can stated as

$$\varphi_{+-} = [(46 \pm 9)^\circ + 590^\circ \times (\Delta m - 0.46)] \text{ sign } (\Delta m)$$

ere Δm is expressed in units of $\hbar\Gamma_S$, and the quoted ror does not include the error in Δm.

iv) The present result is in good agreement with the

Preliminary results have been reported at the Heidel-berg International Conference on Elementary Par-icles. Since then errors in the background subtrac-ions and in the fitting program have been found. Al-hough the quoted result accidentally agrees with the resent one, figs. 5 and 6 of ref. 6 should be disre-garded.

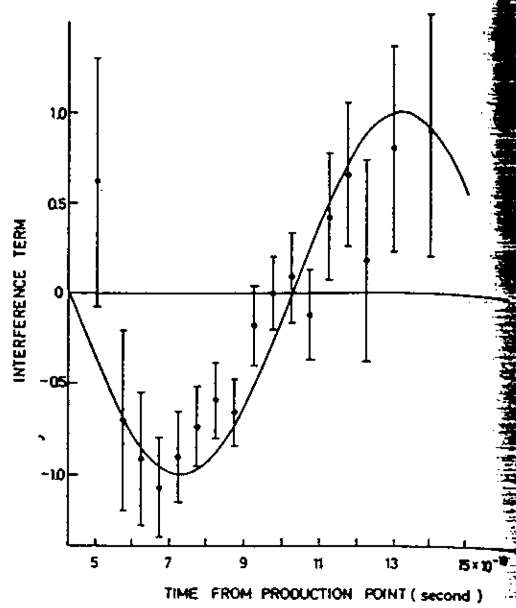


Fig. 5. Experimental data and best fit time distributions manipulated to display the interference term $\cos(\Delta m t - \varphi_{+-})$.

prediction of the "superweak model" of Wolfenstein [9], $\varphi_{+-} = \tan^{-1}(2\Delta m/\Gamma_S) = 42.6^\circ \pm 1.0^\circ$. The somewhat larger value $\varphi_{+-} = 84^\circ \pm 18^\circ$ [2] obtained combining the earlier regeneration experiments [1] and K^+, K^- total cross-section measurements on copper is not confirmed. The regeneration amplitude for copper determined from the 5 000 $K_S \to \pi^+\pi^-$ events comes out $|f(0) - \bar{f}(0)|/k = 2.22 \pm 0.2$ fm^2 at $\langle p \rangle = 2.7$ GeV/c, that is substantially larger than the one $|f(0) - \bar{f}(0)|/k = 1.71 \pm 0.11$ fm^2 employed in ref. 2. This new value can increase the regeneration phase by an amount sufficient to remove the discrepancy. However we do not wish to revise the value of ref. 2 at least until the reason for the discrepancies on the regeneration amplitude is fully understood.

v) Using the value $\varphi_{+-} = 84^\circ \pm 18^\circ$, a satisfactory one constraint fit to the Wu-Yang triangle [10] has been reported by Bennett et al. [11] based on the experimental information available at that time [12,13]

$$2\eta_{+-} + \eta_{00} = 3\epsilon \tag{9}$$

where $\epsilon = (p-q)/(p+q)$ with p, q defined in eq. (2)

$$|\eta_{00}| = A(K_L \to \pi^0\pi^0)/A(K_S \to \pi^0\pi^0)$$

and the condition $\arg(\epsilon) = \arctan(2\Delta m/\Gamma_S)$ following from unitarity, CPT and from neglecting CP violating decay amplitudes in all modes other than the two pi mo.. Repeating the same fit for $\varphi_{+-} = 46^\circ \pm 15^\circ$, it gives the much larger chi-squared of 10.5, corresponding to a confidence level of 10^{-3}.

In order to improve the fit, either a smaller value

for $|\eta_{00}|$ or a different value for δ are experimental information of $|\eta_{00}|$ is ig tain the prediction $|\eta_{00}| = \left(0.7^{+1.0}_{-0.7}\right) \times$ atively starting from $|\eta_{00}|$ and φ_{+-} w = $(4.0 \pm 0.2) \times 10^{-3}$ or $\delta = (-0.1 \pm 0.2) \times 1$

We would like to thank Professo ger who participated in the design a earlier part of this experiment, an W. Paul, P. Preiswerk and H. Faiss port and encouragement. We ackno assistance of Mr. J. Daub and Dr. F who made the measurement of the Luciole possible. Dr. L. Caneschi h the running of the experiment. The paratus was built with the help of M Blythe, K. Bussmann, J. M. Fillot a tori. Finally, we would like to than Petrucci, the CPS staff and especi Hoffmann for the setting up and ope slow ejected proton beam.

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2. C. Rubbia and J. Steinberger, Phys (1967) 531.
3. T. D. Lee, R. Oehme and C. N. Yan 106 (1957) 340.
4. W. F. Baker, R. L. Cool, E. W. Jen S. L. Lindenbaum, W. A. Love, D. I derer, S. Ozaki, A. L. Read, J. J. F L. C. L. Yuan, Phys. Rev. Letters

$$|\eta_{+-}| = \left|\frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^0\pi^0)}\right| = 2.285 \pm .019 \times 10^{-3}$$

$$\varphi_{+-} = 43.5 \pm 0.6^\circ$$

$$|\eta_{00}| = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = 2.275 \pm .019 \times 10^{-3}$$

$$\varphi_{00} = 43.4 \pm 1.0^\circ$$

$$\eta_{+-} = \epsilon + \epsilon'$$

$$2\,\mathrm{Re}\,\epsilon = 3.04 \pm 0.25 \times 10^{-3} \quad \pi\mu\nu$$

$$3.33 \pm 0.14 \times 10^{-3} \quad \pi e\nu$$

$$\epsilon' = \frac{i}{\sqrt{2}}\,\mathrm{Imag}\left(\frac{A_2}{A_0}\right) e^{i(\delta_2 - \delta_0)}$$

$$\frac{\epsilon'}{\epsilon} = 7.4 \pm 5 \pm 3 \times 10^{-4} \quad \text{E731}$$

$$= 33 \pm 11 \times 10^{-4} \quad \text{NA31}$$

$$= 20 \pm 7 \times 10^{-4} \quad \text{NA31}$$

$$= 28 \pm 4.1 \times 10^{-4} \quad \text{KTEV}$$

3(stat) 1.0(mc) 2.6(syst)

Search for Coherent Regeneration from Electrons: the K^0 charge radius

Phys Letters
30 B 276 (1969)

no evidence but interesting limits

$\langle R^2 \rangle = -.05 \pm 0.13 \times 10^{-26}$ cm^2

VDM $\langle R^2 \rangle = 0.076 \times 10^{-26}$ cm^2.

Relevant to CP but not in the K system.

In UA1 first evidence for $B\bar{B}$ mixing
P.L. B 186 (1987) 247

Perils of Modern Living

Harold P. Furth

Well up above the tropostrata
There is a region stark and stellar
Where, on a streak of anti-matter
Lived Dr. Edwrd Anti-Teller.

Remote from Fusion's origins
He lived unguessed and unawares
With all his antikith and kin,
And kept macassars on his chairs.

One morning, idling by the sea,
He spied a tin of monstrous girth
That bore three letters: A.E.C.
Out stepped a visitor from earth.

Then, shouting gladly o'er the sands,
Met two who in their alien ways
Were like as lentils. Their right hands
Clasped, and the rest was gamma rays.

The New Yorker, 1955

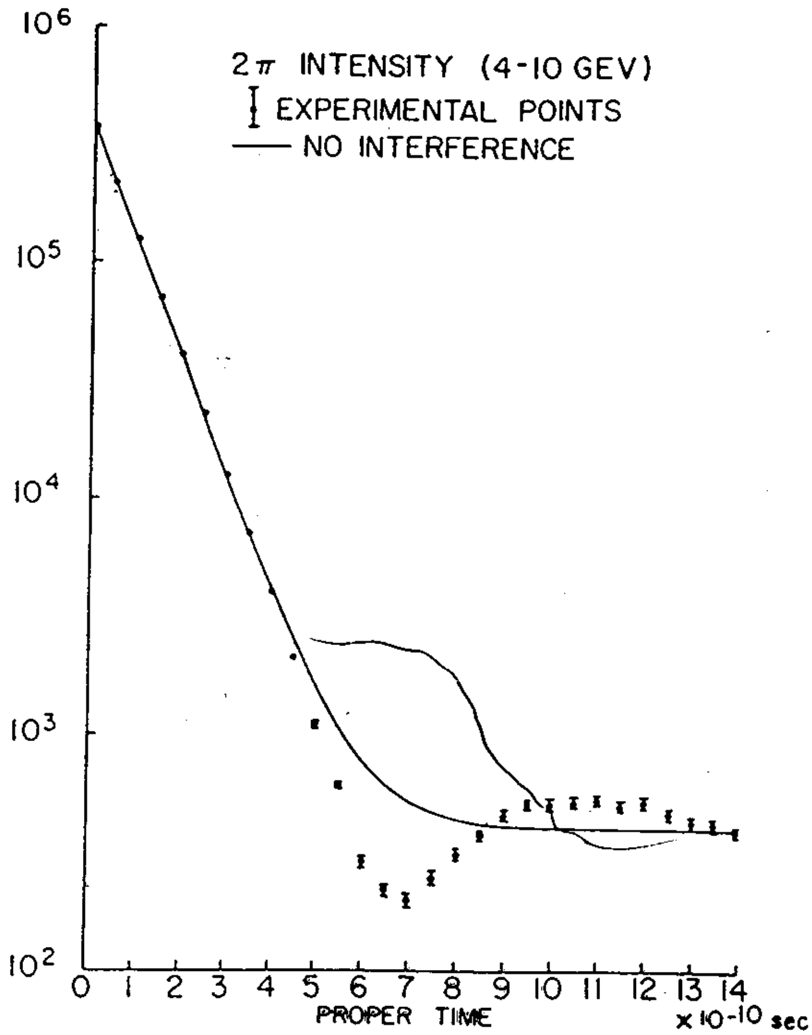

FIG. 2. Yield of $\pi^+\pi^-$ events as a function of proper time downstream from an 81 cm carbon regenerator placed in a K_L beam. Figure taken from thesis of T. Modis, Columbia University (1973); a published version of this work is given by Carithers *et al*. (1975).