The Discovery of CP Violation: a Surprise!

James W. Cronin
CERN Symposium
December 4, 2009

Spring 1954 University of Chicago

In a 4th floor classroom in the Ryerson Physical Laboratory Murry Gell-Mann gave a series of lectures on the strange particles

Enrico Fermi attended these lectures

In his classification appeared:

θ° S = +1 } conserved in
$\overline{\theta}^\circ$ S = -1 } strong interaction

both decay to $\pi^+ \pi^-$ } weak interaction

As best I remember Fermi asked:

"If θ° and $\overline{\theta}^\circ$ both decay into $\pi^+\pi^-$ how can they be different?"

This remark played a role in the famous Gell-Mann - Pais paper

PHYSICAL REVIEW VOLUME 97, NUMBER 5 MARCH 1, 1955

Behavior of Neutral Particles under Charge Conjugation

M. Gell-Mann,* *Department of Physics, Columbia University, New York, New York*

AND

A. Pais, *Institute for Advanced Study, Princeton, New Jersey*

(Received November 1, 1954)

At any rate, the point to be emphasized is this: a neutral boson may exist which has the characteristic θ^0 mass but a lifetime $\neq \tau$ and which may find its natural place in the present picture as the second component of the θ^0 mixture.

One of us, (M. G.-M.), wishes to thank Professor E. Fermi for a stimulating discussion.

$\theta_0 \quad S = +1$

$\bar{\theta}_0 \quad S = -1$

$$\theta_1 = \frac{1}{\sqrt{2}}(\theta_0 + \bar{\theta}_0)$$

$$\theta_2 = \frac{1}{\sqrt{2}}(\theta_0 - \bar{\theta}_0)$$

States of definite lifetime

If $\theta_1 \rightarrow \pi^+ \pi^-$

$\theta_2 \not\rightarrow \pi^+ \pi^-$ <u>only</u> 3 body

Based on C

after Jan 1957 CP

$\tau_2 \gg \tau_1 \sim 5 \times 10^{-8}$ sec

1) A long lived neutral meson

2) Particle mixture phenomena
   - a Transport of ±1 Strangeness to large distance
   - b Regeneration
   - c Oscillatory phenomena

3) Sensitive test for CP

PHYSICAL REVIEW VOLUME 100, NUMBER 5 DECEMBER 1, 1955

Note on the Decay and Absorption of the θ^0†

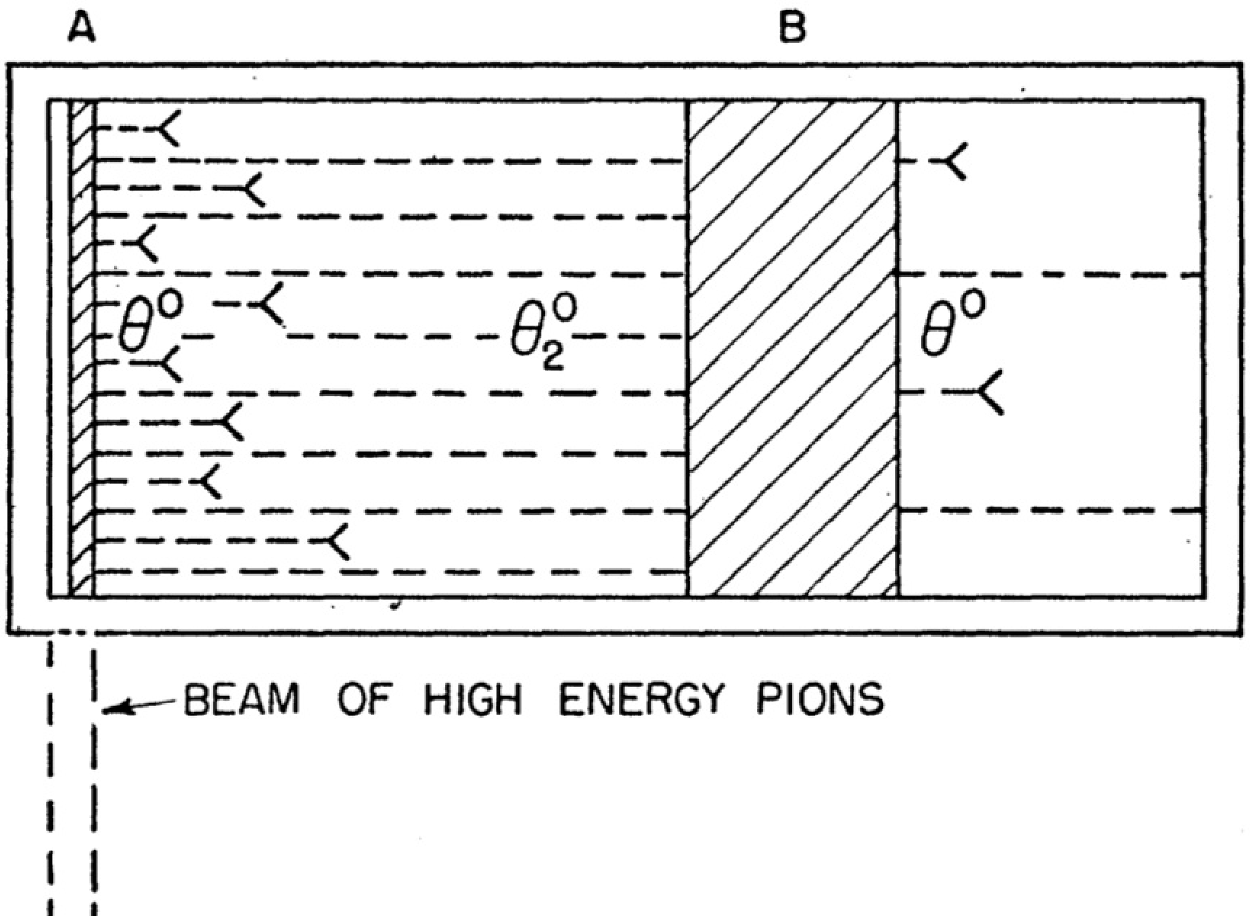
A. PAIS,* *Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York*

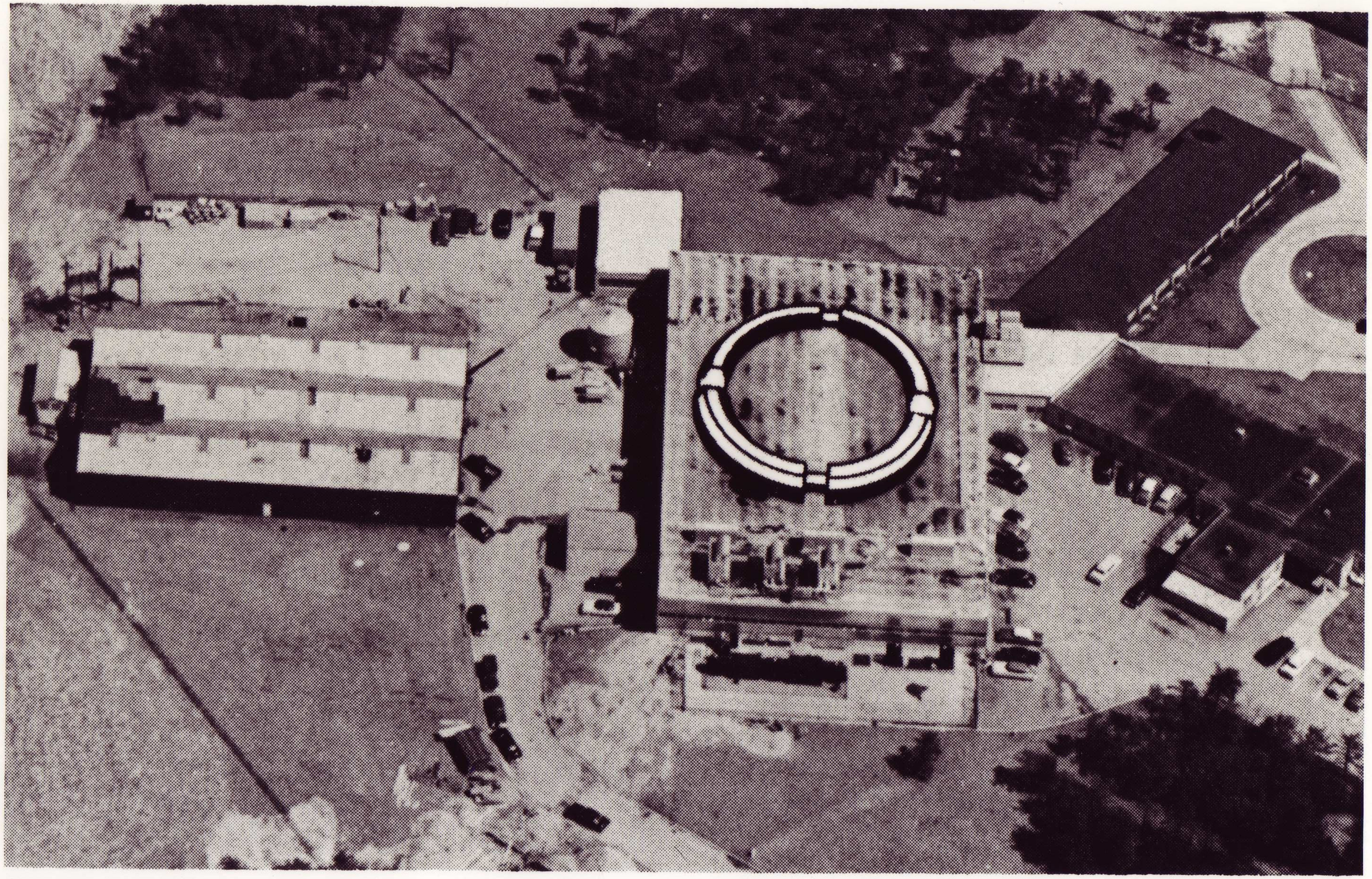
AND

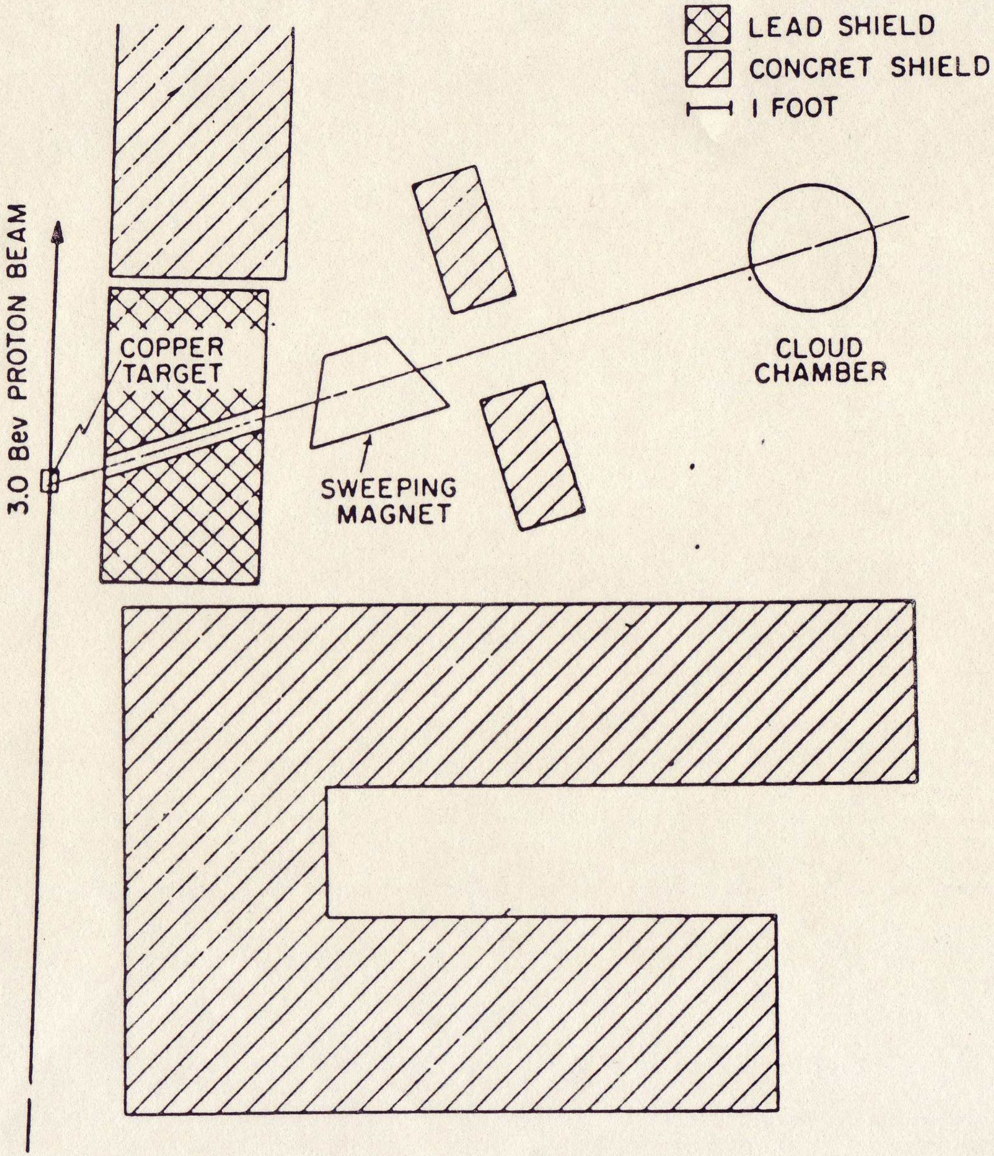
O. PICCIONI, *Brookhaven National Laboratory, Upton, New York*

(Received July 5, 1955)

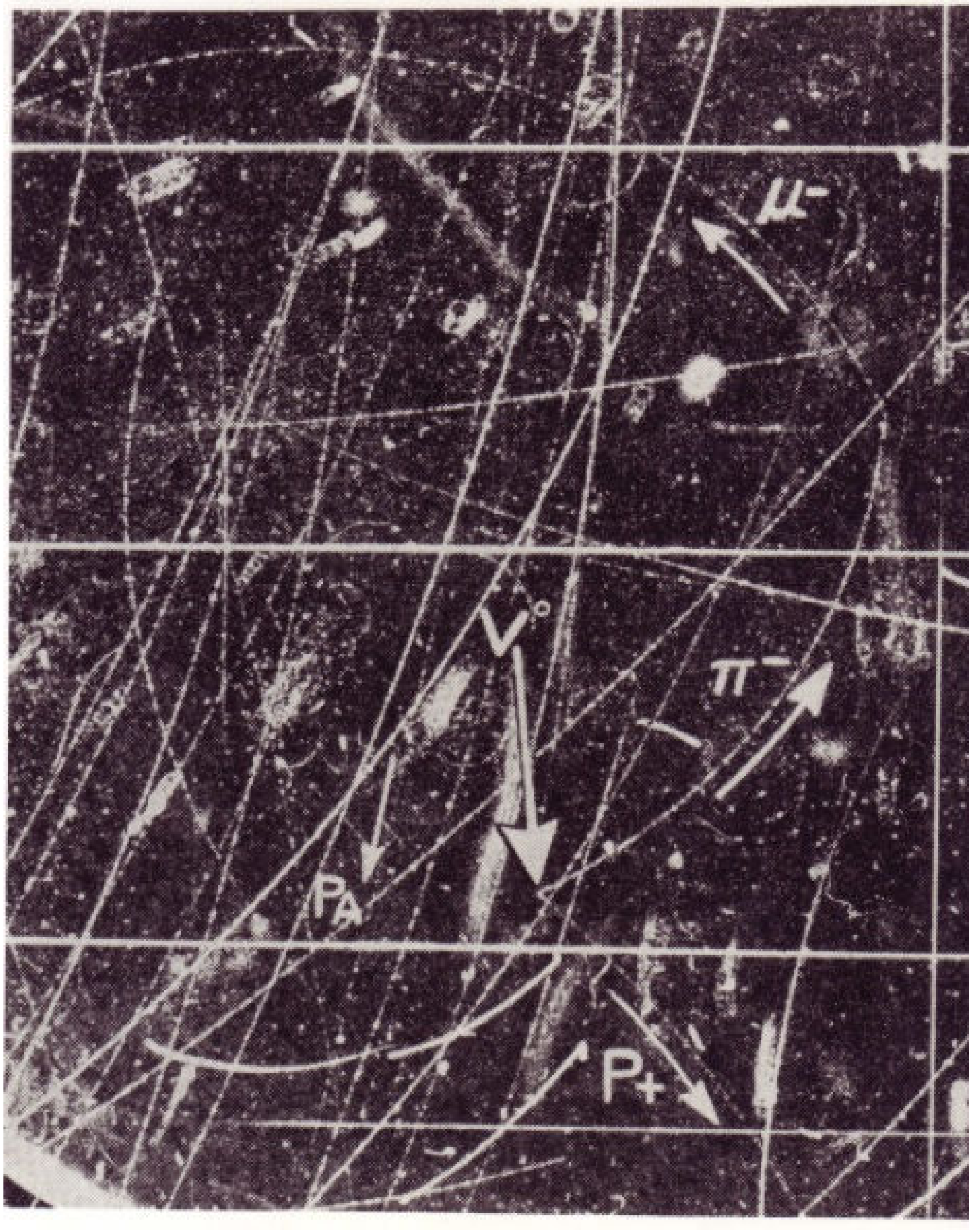
A suggestion is made on how to verify experimentally a recent theoretical suggestion that the θ^0 meson is a "particle mixture."







LEAD SHIELD
CONCRET SHIELD
1 FOOT
3.0 Bev PROTON BEAM
COPPER TARGET
SWEEPING MAGNET
CLOUD CHAMBER


μ⁻
V°
π⁻
PA
P+

Observation of Long-Lived Neutral V Particles*

K. LANDE, E. T. BOOTH, J. IMPEDUGLIA, AND L. M. LEDERMAN,
Columbia University, New York, New York

AND

W. CHINOWSKY, *Brookhaven National Laboratory, Upton, New York*

(Received July 30, 1956)

The authors are indebted to Professor A. Pais whose elucidation of the theory directly stimulated this research. The effectiveness of Cosmotron staff collaboration is evidenced by the successful coincident operation of six magnets and the Cosmotron with the cloud chamber.

PHYSICAL REVIEW VOLUME 124, NUMBER 4 NOVEMBER 15, 1961

Regeneration of Neutral K Mesons and Their Mass Difference*

R. H. Good,† R. P. Matsen,‡ F. Muller,§ O. Piccioni,|| W. M. Powell,
H. S. White, W. B. Fowler,** and R. W. Birge††
Lawrence Radiation Laboratory, University of California, Berkeley, California
(Received June 23, 1961)

INTRODUCTION

IT is by no means certain that, if the complex ensemble of phenomena concerning the neutral K mesons were known without the benefit of the Gell-Mann–Pais theory,[1] we could, even today, correctly interpret the behavior of these particles. That their theory, published in 1955, actually preceded most of the experimental evidence known at present, is one of the most astonishing and gratifying successes in the history of the elementary particles. They advanced the hypothesis that the two mesons, K^0 and $\bar{K}^0$, are states of definite strangeness but not of definite mean life. The states which decay with a definite mean life and which, also, have a definite mass value are two other mesons, K_1 and K_2.

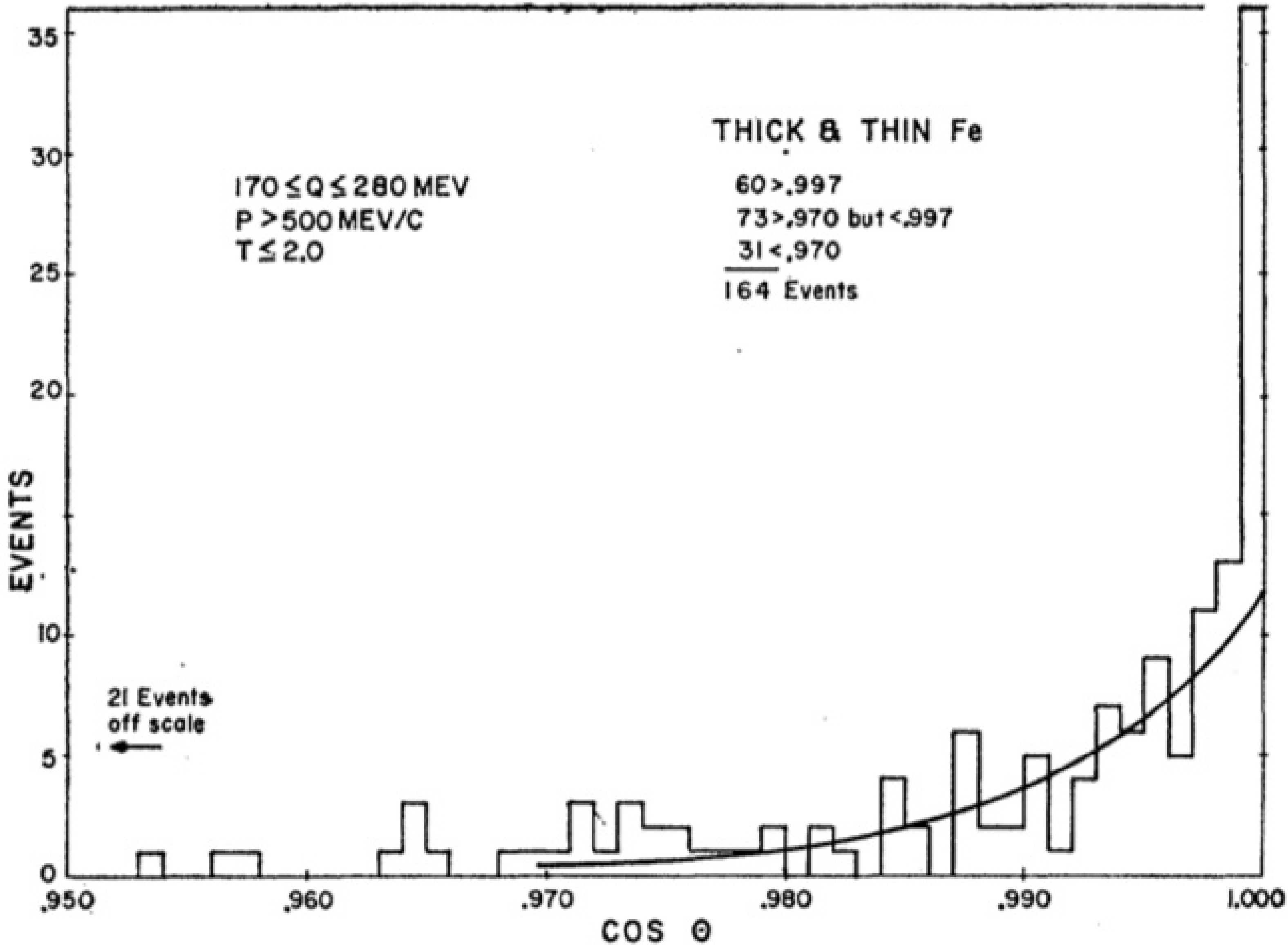


FIG. 17. Angular distribution of all events that originate in either the 6-in. or the $1\frac{1}{2}$-in. iron plate and that satisfy the criteria $170 \leq Q \leq 280$ Mev, $P > 500$ Mev/c, and $T \leq 2.0$ mean lives.

DECAY PROPERTIES OF K_2^0 MESONS*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov
Joint Institute of Nuclear Research, Moscow, U.S.S.R.
(Received April 20, 1961)

Combining our data with those obtained in reference 7, we set an upper limit of 0.3% for the relative probability of the decay $K_2^0 \to \pi^- + \pi^+$. Our results on the charge ratio and the degree of the 2π-decay forbiddenness are in agreement with each other and provide no indications that time-reversal invariance fails in K^0 decay.

PHYSICAL REVIEW VOLUME 132, NUMBER 5 1 DECEMBER 1963

Anomalous Regeneration of $K_1{}^0$ Mesons from $K_2{}^0$ Mesons*

L. B. Leipuner, W. Chinowsky,† and R. Crittenden
Brookhaven National Laboratory, Upton, New York

and

R. Adair,‡ B. Musgrave,§ and F. T. Shively†
Yale University, New Haven, Connecticut

(Received 13 March 1963; revised manuscript received 27 August 1963)

A beam of 1.0-BeV/c $K_2{}^0$ mesons passing through liquid hydrogen in a bubble chamber was seen to generate $K_1{}^0$ mesons with the momentum and direction of the original beam. The intensity of $K_1{}^0$ production was far greater than that anticipated from conventional mechanisms, and the suggestion is made that the $K_1{}^0$ mesons are produced by coherent regeneration resulting from a new weak long-range interaction between

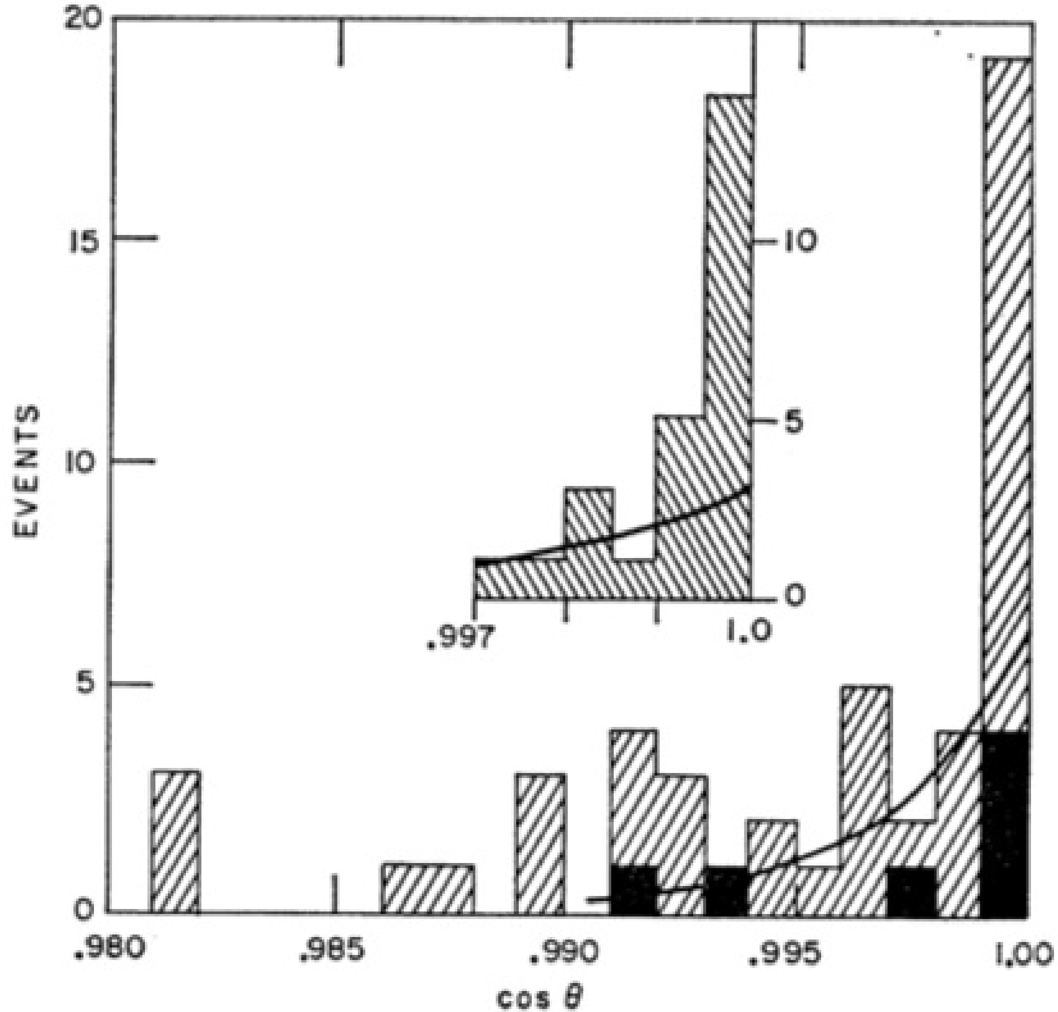


FIG. 3. Angular distribution of events which have a 2π-decay Q value consistent with K_1^0 decay, and a momentum consistent with the beam momentum. θ is the angle between the total visible momentum and the incident beam. All events are plotted for which 180 MeV$\leq Q \leq$270 MeV, $p \geq$800 MeV/c. The black histogram presents those events in front of the thin window. The solid curve represents the contribution expected from K_2^0 decays.

Dipion Production at Low Momentum Transfer in π^{-}-p Collisions at 1.5 BeV/c*

A. R. Clark,† J. H. Christenson,‡ J. W. Cronin, and R. Turlay§

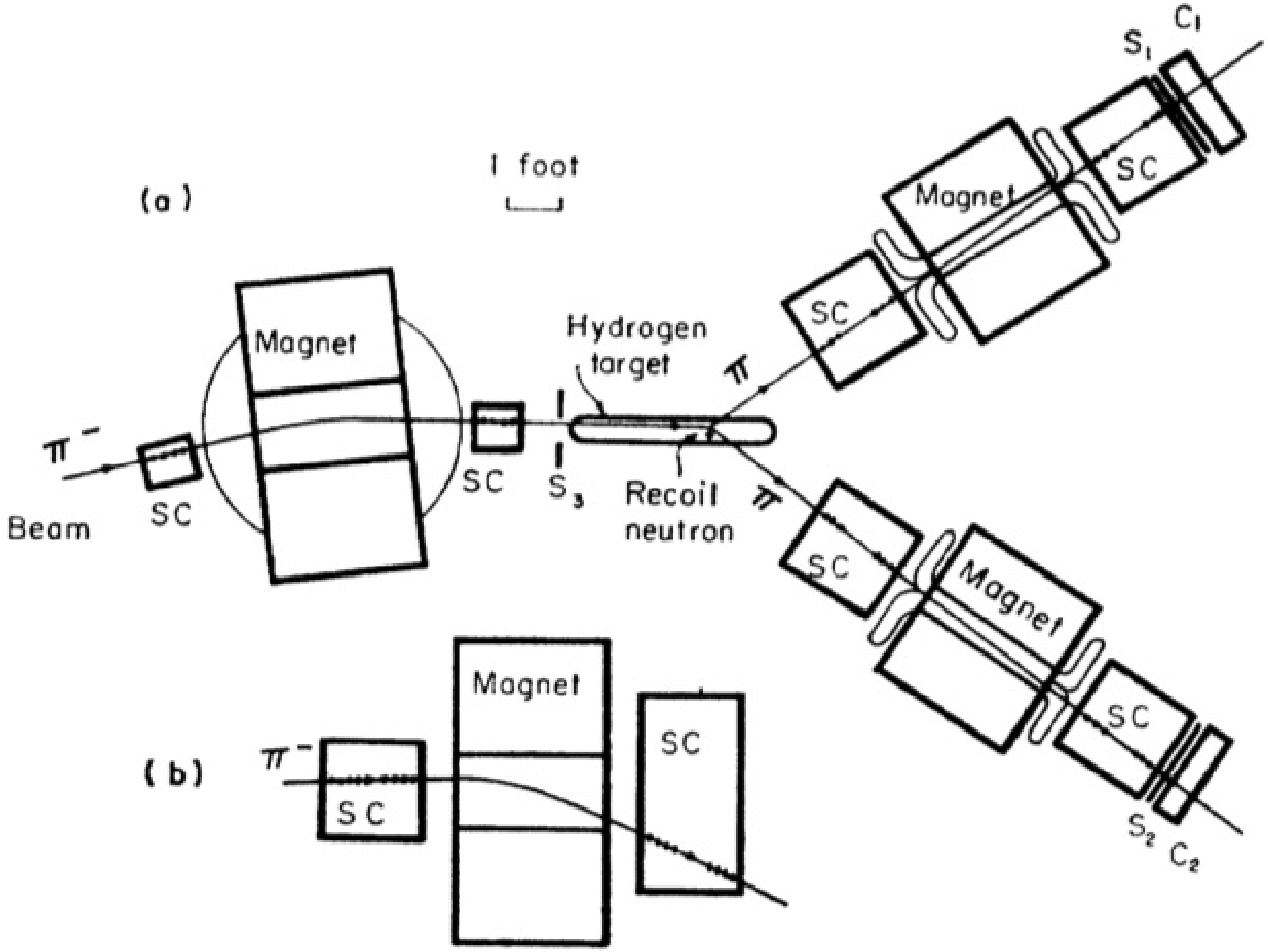


FIG. 1. Schematic views of the experimental apparatus. (a) Plan view, showing all spark chambers and analyzing magnets; (b) side view of one decay pion spectrometer. "SC" denotes spark chamber.

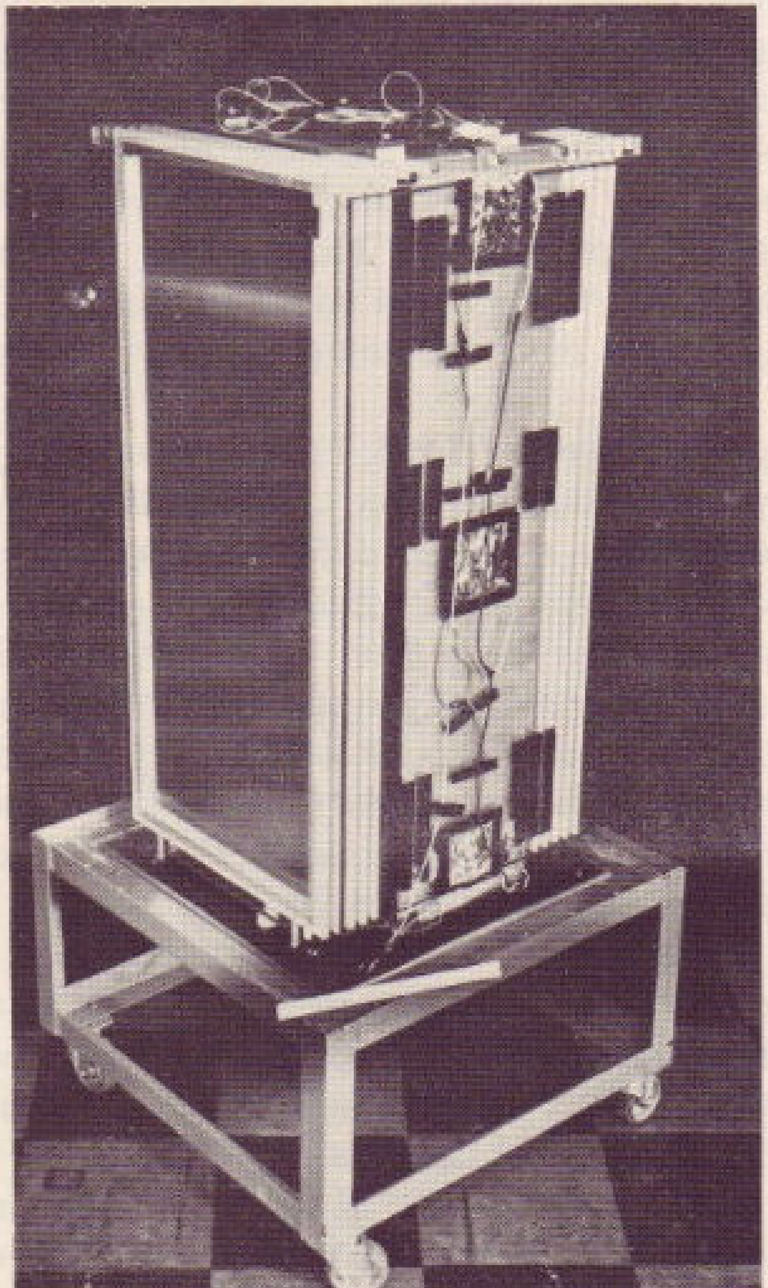


FIG. 26. View of thin foil chamber constructed at Princeton University.

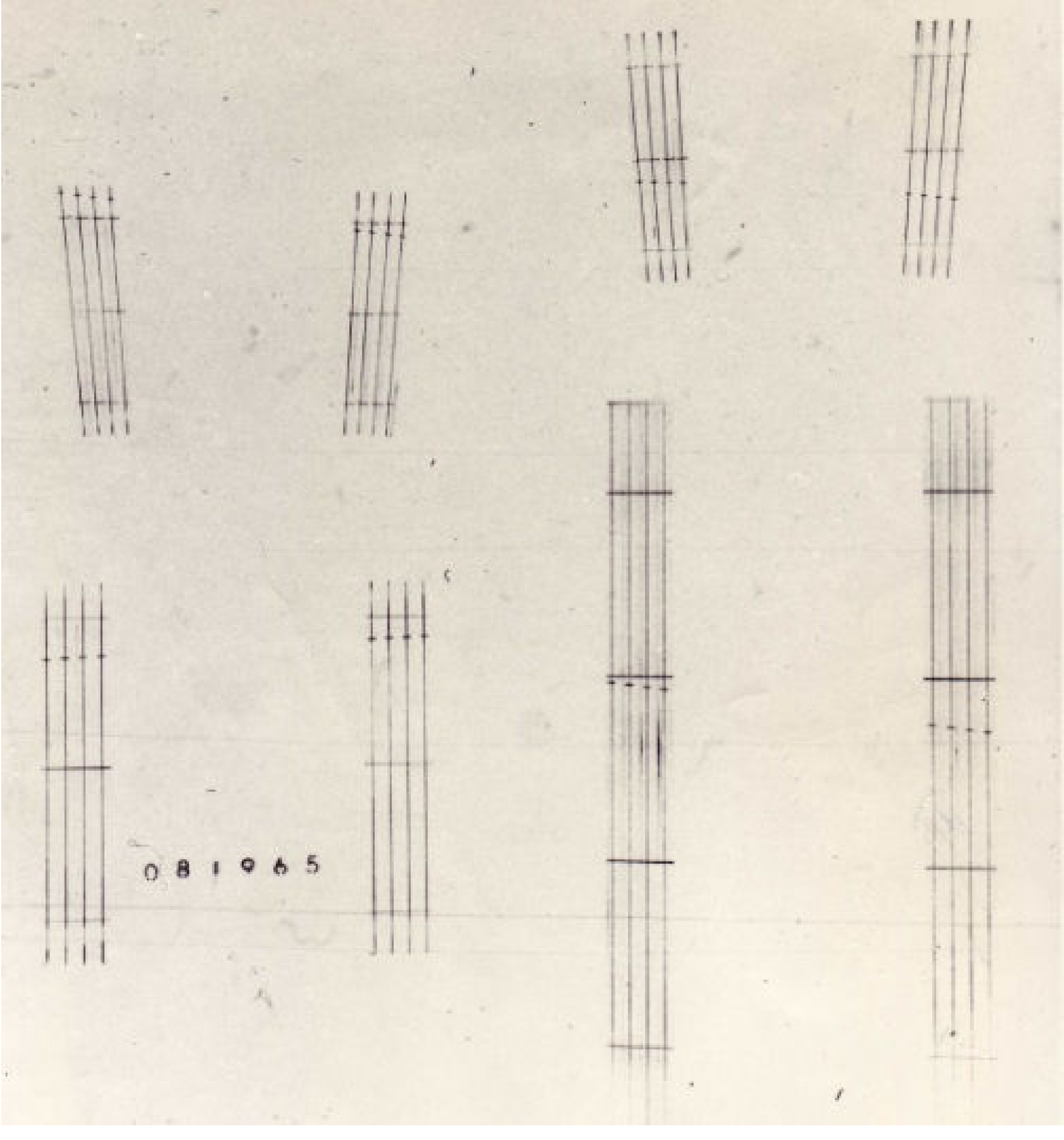

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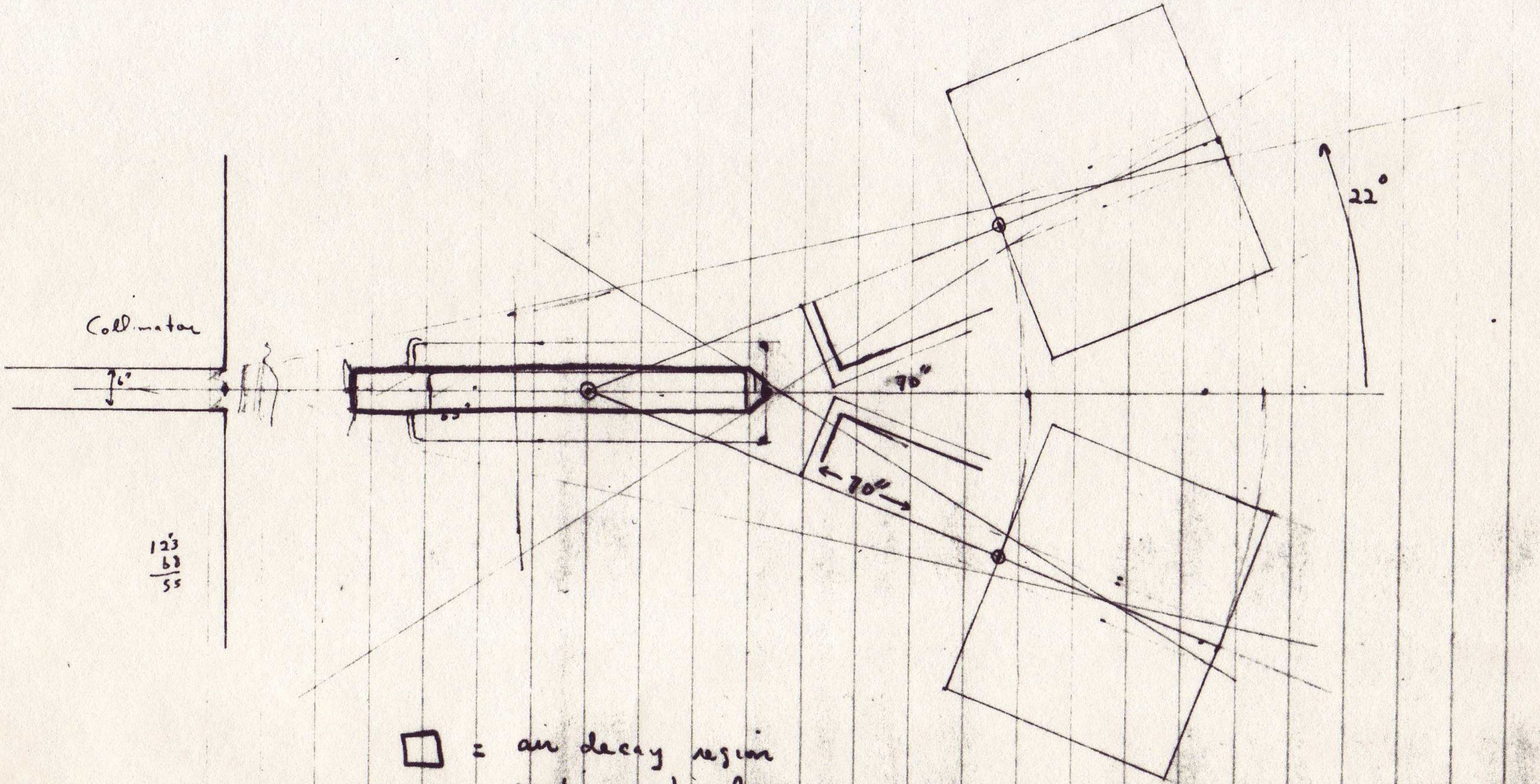
Fig 1



☐ = air decay region used in monte carlo calculation

PROPOSAL FOR K^o_2 DECAY AND INTERACTION EXPERIMENT

J. W. Cronin, V. L. Fitch, R. Turlay

(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 $K^o_2 \to \pi^+ + \pi^-$, a new limit for the presence (or absence) of neutral currents as observed through $K_2 \to \mu^+ + \mu^-$. 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

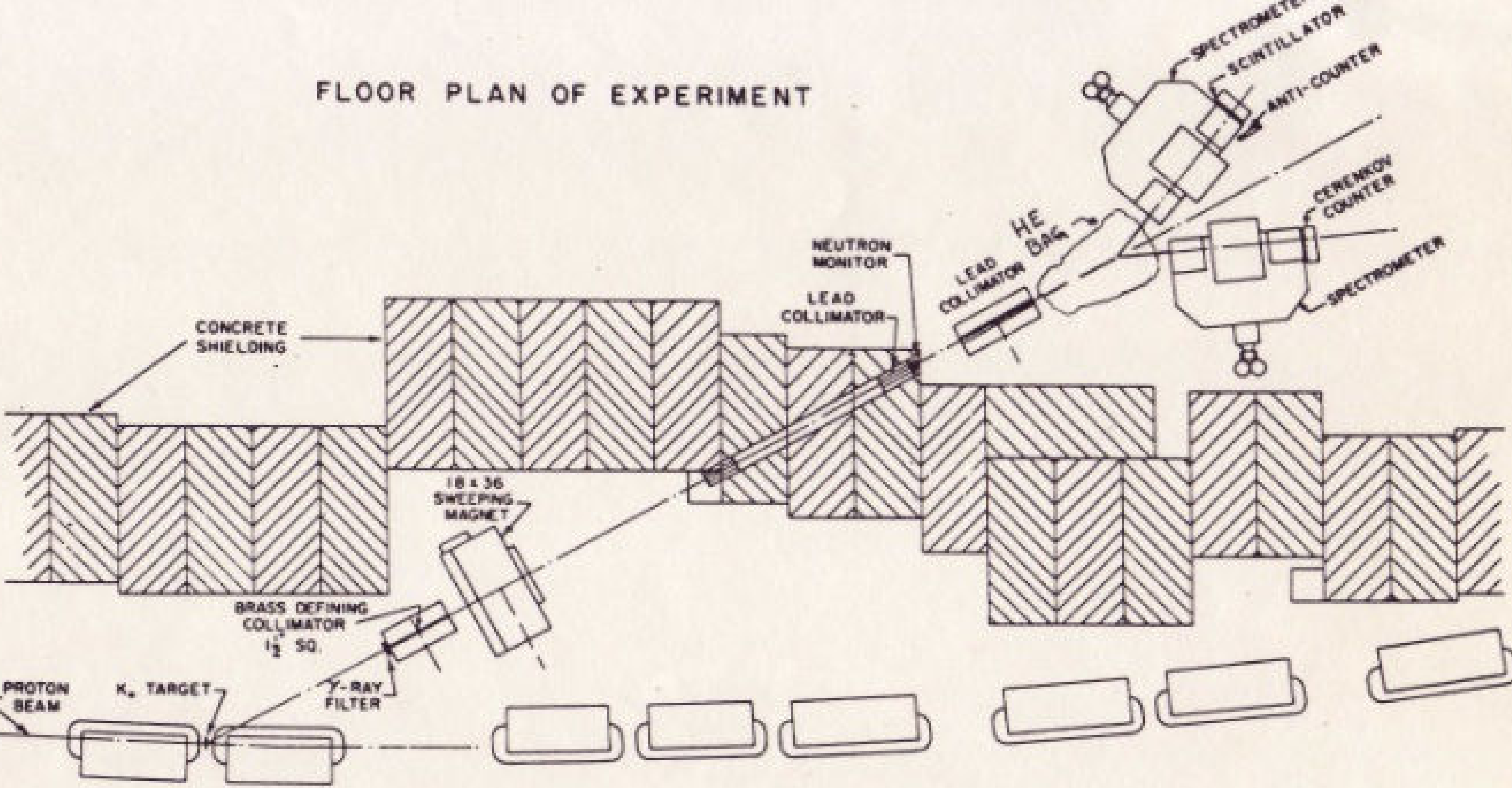
We have made careful Monte Carlo calculations of the counting rates expected. For example, using the 30° beam with the detector 60-ft. from the A.G.S. target we could expect 0.6 decay events per 10^{11} circulating protons if the K_2 went entirely to two pions. This means that one can set a limit of about one in a thousand for the partial rate of $K_2 \to 2\pi$ 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.

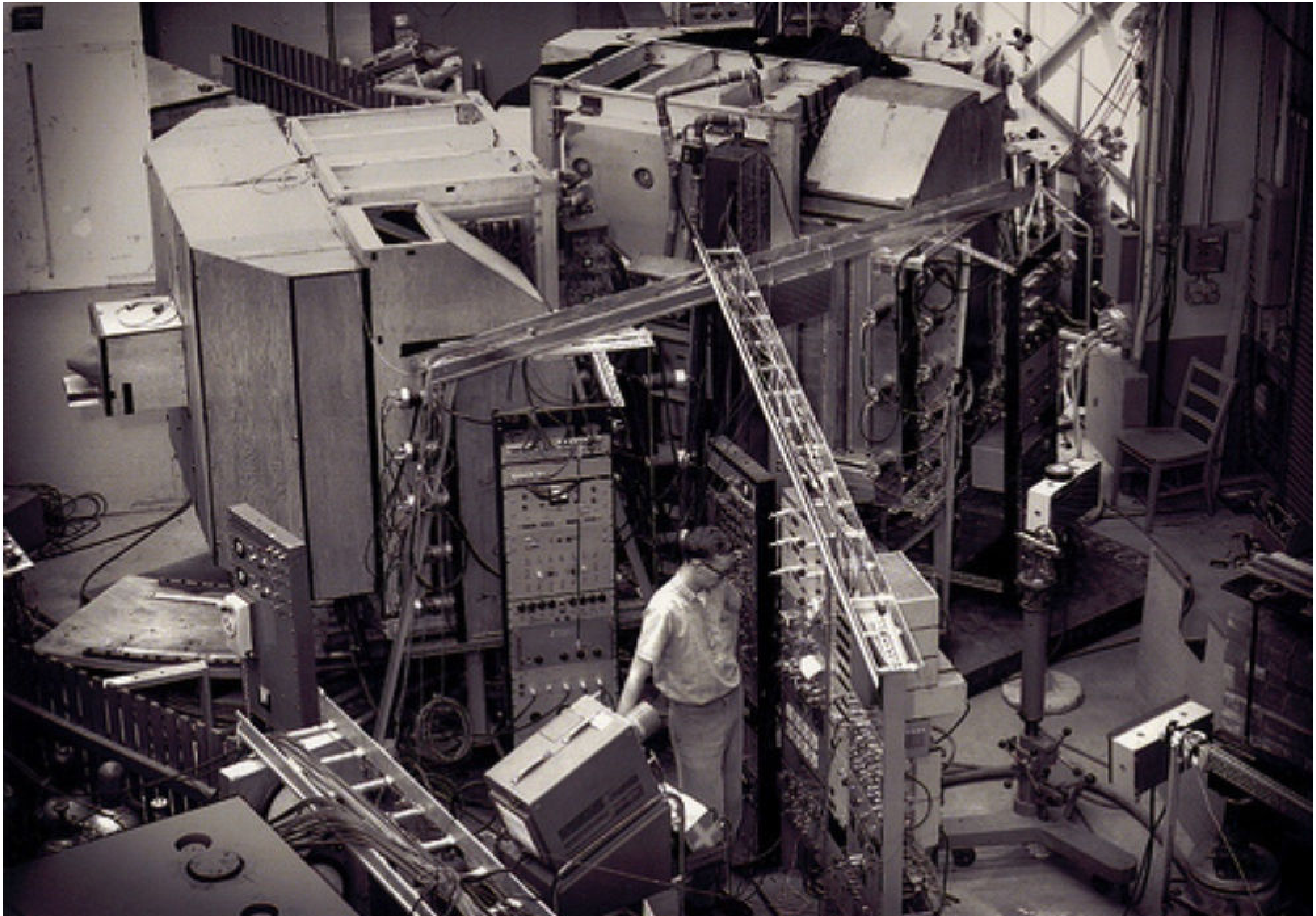
If the experiment of Adair, et al. is correct the rate of coherently regenerated K_1's in hydrogen will be approximately 80/hour. This is to be compared with a total of 20 events in the original experiment. The apparatus has enough angular acceptance to detect incoherently produced K_1's with uniform 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.

FLOOR PLAN OF EXPERIMENT





Remember that each neutron count (ie 10^5) : $.10^6\ K_o^2$ in 1 Bev/c momentum band

Now we computed that if all K_o^2 decayed by K_o^1 decay mode we'd have 0.06/ pulse / 10^{11} 1000

$\frac{240}{10^5\ 8}$ = 30×10^{-5} or $\sim 3 \times 10^{-4} \times$ fraction that decay in 1.8 meters $\sim 3 \times .05 = .15 \times 10^{-4} \sim 1.5\ 10^{-5}$

efficiency for a 1 Bev/c momentum spread about 1.1 Bev/c

Recall $10^6\ K_o^2$/ neutron count $\times 1.5 \times 10^{-5}$

∴ Set limit of $\frac{1}{15}$ per (100) neutron count $\frac{1}{1500}$

or .066 per neutron count.

∴ Want for helium bag ~ $\frac{10^4}{15}$ = 666 neutron counts

Make 1200 for conservatism.

Thus want ~ 1200 neutron counts for CP invariance test.

.06 / 1000

THURSDAY – JUNE 20, 1963 – CP INVARIANCE RUN

Have removed regenerator stand and anti and installed Helium bag – bag touches S.C. counters and falls ~6" short of collimator
bag is .010" thick – switched Newman to new H.V. supply – same voltage.

126921 126945 .541 .525 .256 – .524 151 1.746

64437 63261

Stopped run because neutron mon not counting – found anti and collector transistors blown in coinc. circuit – replaced – AOK

126945 – 127262 ~~[illegible]~~ 54469 5.3162 2.495 30.011 – 12543 317 1382 15.248 .508 1023 21.7 .1816 .1772 .0830 10.6 2.390 AT N127355 DIAL 36

3a is now meaningless – won't write

127262 128412 ~~1789~~ ~~2.088~~ 17.57 8.098 100.02 41.62 1150 6509 49.192 .492 .179 .179 .081 11.50 2.40 ← Made adjustment Monitor Voltage this run

Should consider changing Pb filter – now $2\frac{9}{16}$" ??

128412 128604 278 105 16.41 6.28 997 2588

camera advanced 10 pulses at this point – counts not reset.

128614 129611 18525 18.136 7.994 100.02 41.72 997 5890 49.48 .495 .185 .181 .0994 9.97 2.40

13

129611 130805 18.504 18.166 8.262 100.12 41.92 1194 5553 49.923 .498 .185 .182 .0826 11.9 2.40 130151 10 pm

130805 131535 2.014 11.754 5367 64.597 26.894 730 2981 32.215 .498 16.2 .186 .1815 .0832 11.3 2.41 63330

Film ran out some time (?) before this – noticed it at this point – Somewhat before 131700 it would seem! Sorry.

← Changed film & began again

131545 132626 – 12696 7788 76.641 40.162 1081 6897 47.965 .496 (#3 rate) – 14.0 – .183 .0806 11.2 2.40

at 0445, (~131844) noticed rubber diaphragm in camera lens work off – perhaps pictures taken till now are no good?

found top of Helium bag in beam at end of above run – put more He in.

132626 133813 – 13.281 7.966 100.019 41.909 1187 6124 49.743 .497 – 16.3 – .183 .080 11.9 2.39 – SAME DIAL – 36

Spare at 133100 134650, 136200, change at 137750 – Watch end closely!

N133262 – Spaced film

133813 64451 63253 ~~64530~~ ~~63303~~ DIAL →

Note: meg dropped too – corrected Ball + NME – don't like it, but so what.

At 134650 – Spaced film – put some helium in bag at 12:45

63.266

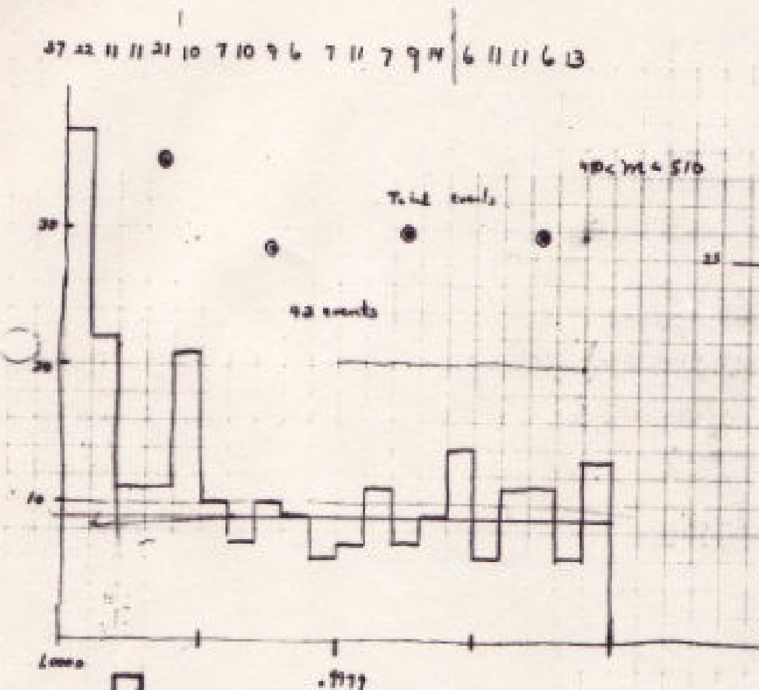
CP limit $\frac{42}{18300} = 2.3 \times 10^{-3}$

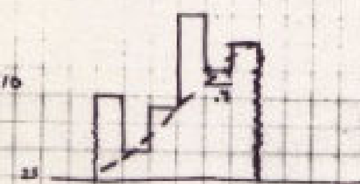
$= 1 \times 10^{-3}$

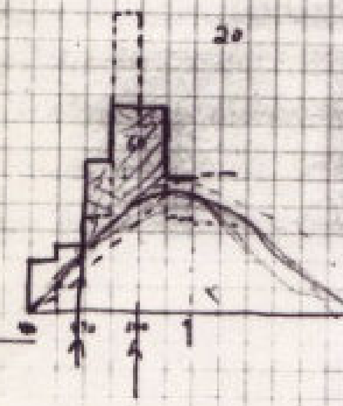
Some plots of 5211 CP events

$\left[K_2^0 \to \pi^+ \pi^- \gamma \right|$?? phase space $\frac{1}{\alpha}$

To draw final conclusions we await the remeasurement on the Hybd.
5211



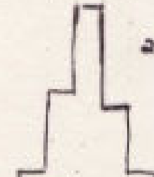




An inter

New spectrum

cos θ > .99995



28 events K_1^0

Tail of K(eπν) spectrum with zero neutrino momentum

Note scale!

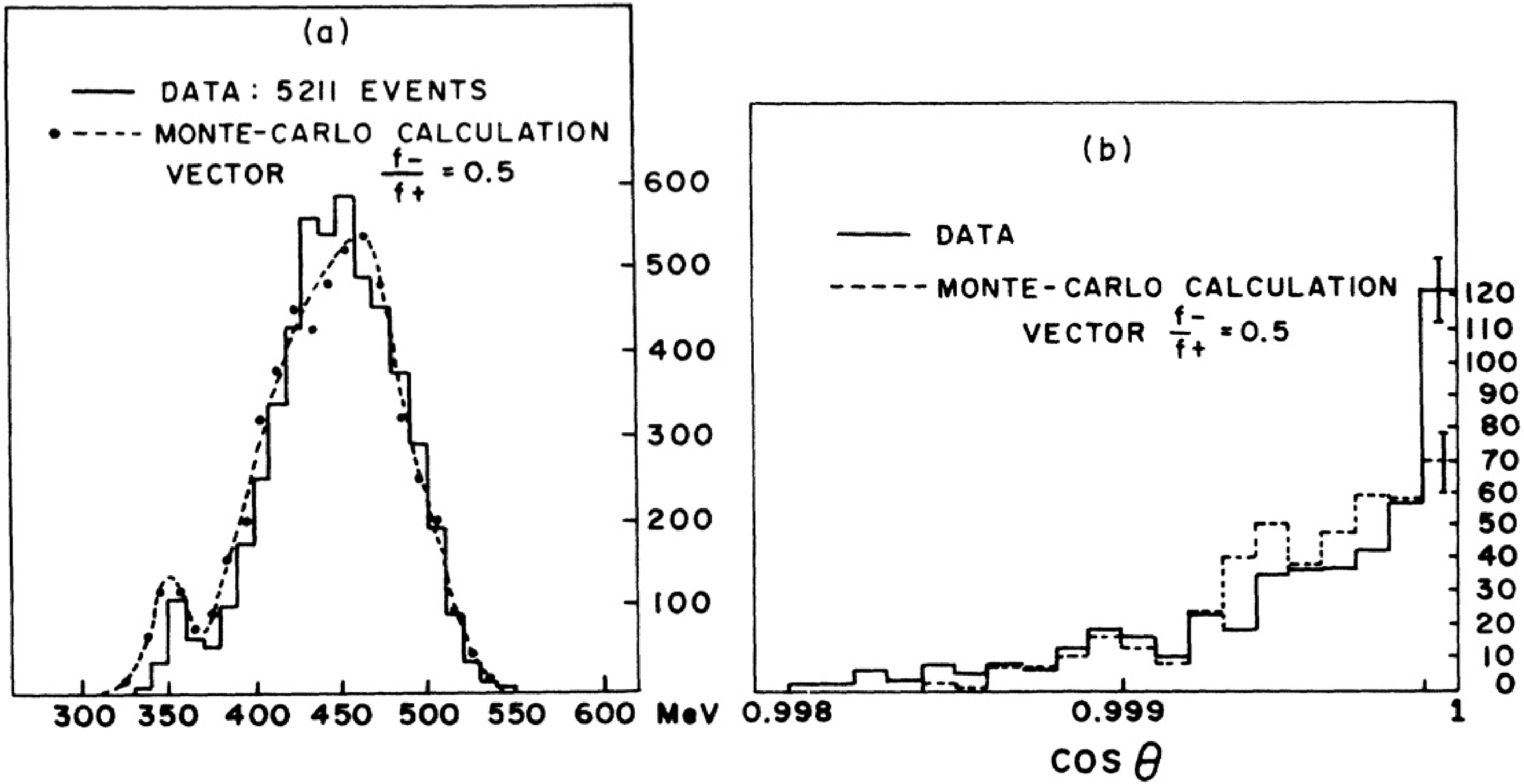
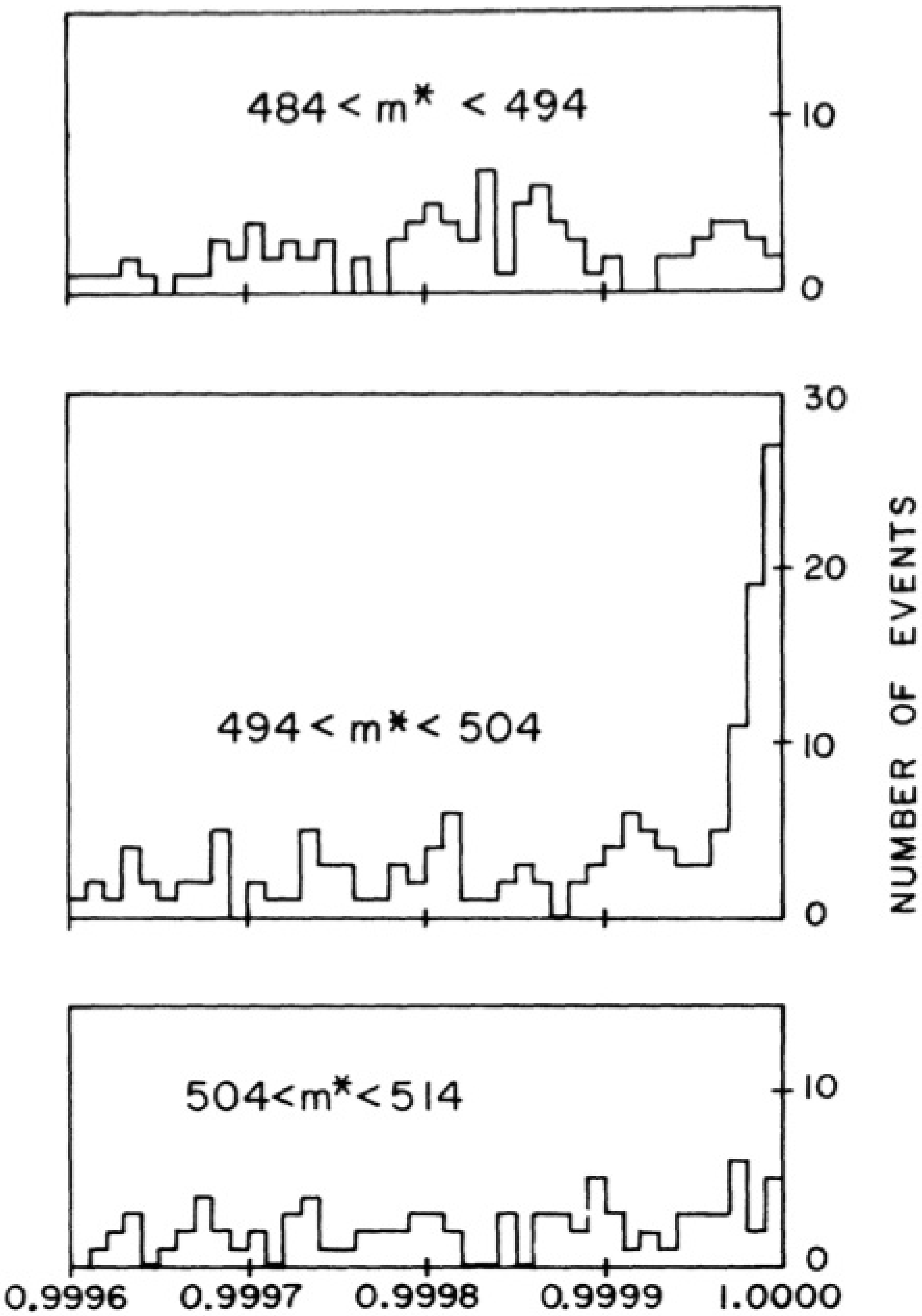


FIG. 2. (a) Experimental distribution in m^* compared with Monte Carlo calculation. The calculated distribution is normalized to the total number of observed events. (b) Angular distribution of those events in the range $490 < m^* < 510$ MeV. The calculated curve is normalized to the number of events in the complete sample.



484 < m* < 494
494 < m* < 504
504 < m* < 514
NUMBER OF EVENTS
0
10
20
30
0.9996
0.9997
0.9998
0.9999
1.0000

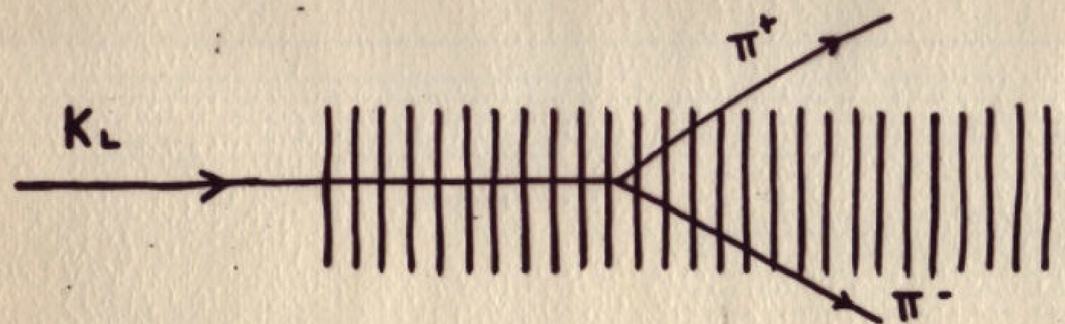
EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

We would conclude therefore that K_2^0 decays to two pions with a branching ratio $R = (K_2 \rightarrow \pi^+ + \pi^-)/(K_2^0 \rightarrow \text{all charged modes}) = (2.0 \pm 0.4) \times 10^{-3}$ where the error is the standard deviation. As emphasized above, any alternate explanation of the effect requires highly nonphysical behavior of the three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as

EVIDENCE FOR CONSTRUCTIVE INTERFERENCE BETWEEN COHERENTLY REGENERATED AND *CP*-NONCONSERVING AMPLITUDES*

V. L. Fitch, R. F. Roth, J. S. Russ, and W. Vernon
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received 3 June 1965)



$$y(\pi^+\pi^-) \sim |A_r + \eta_{+-}|^2$$

$$\eta_{+-} = \frac{\text{amp}\,(K_L \rightarrow \pi^+\pi^-)}{\text{amp}\,(K_s \rightarrow \pi^+\pi^-)}$$

$$A_r = i\pi N\Lambda\left(\frac{f-\bar{f}}{k}\right)\left(i\delta + \frac{1}{2}\right)^{-1}$$

For $A_r = \eta_{+-}$
rate = 4 × rate
for $A_r = 0$
Constructive
interferance

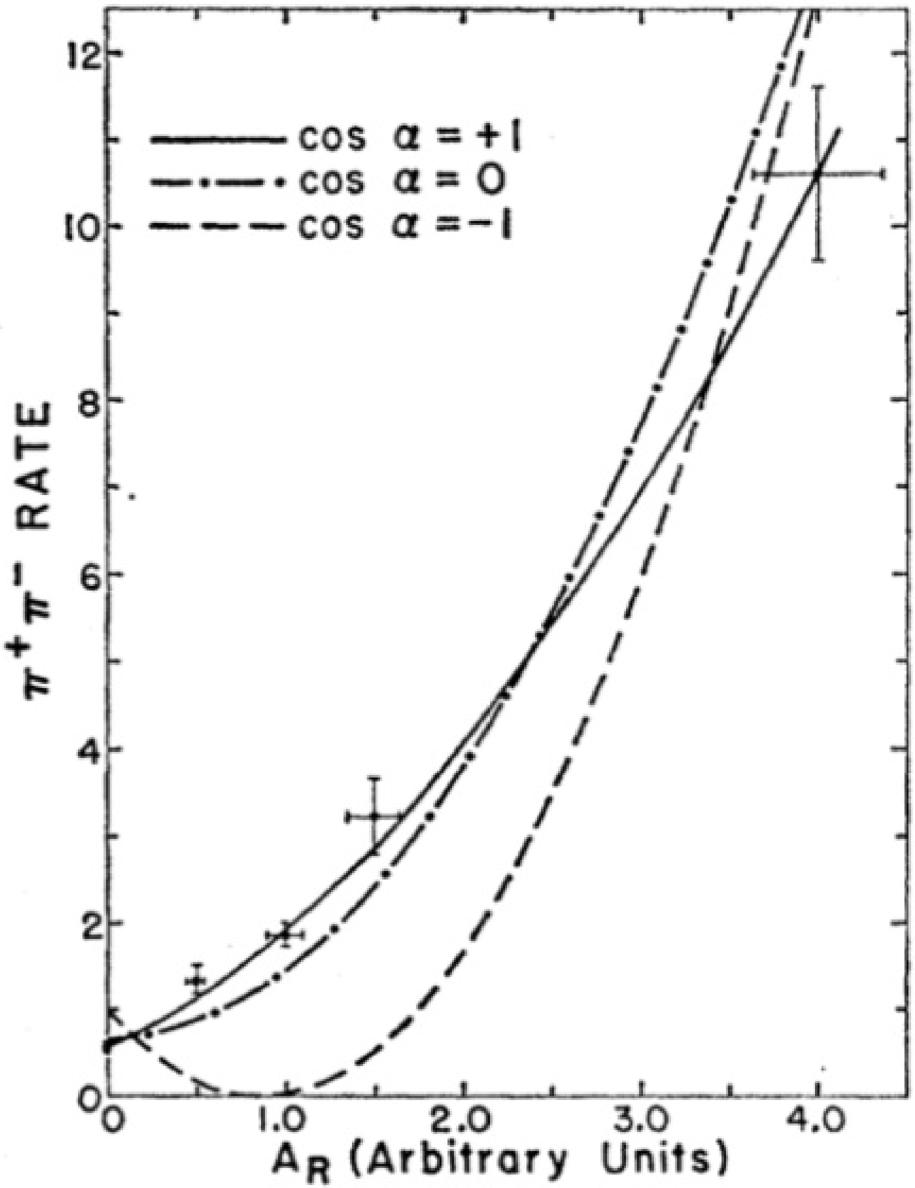


FIG. 13. Measured event rate as a function of regeneration amplitude. The solid curves are the results of best χ^2 fits to the data for interference angles of 0, $\pi/2$, and π. Only the curve for 0 angle gives a good fit to the data.

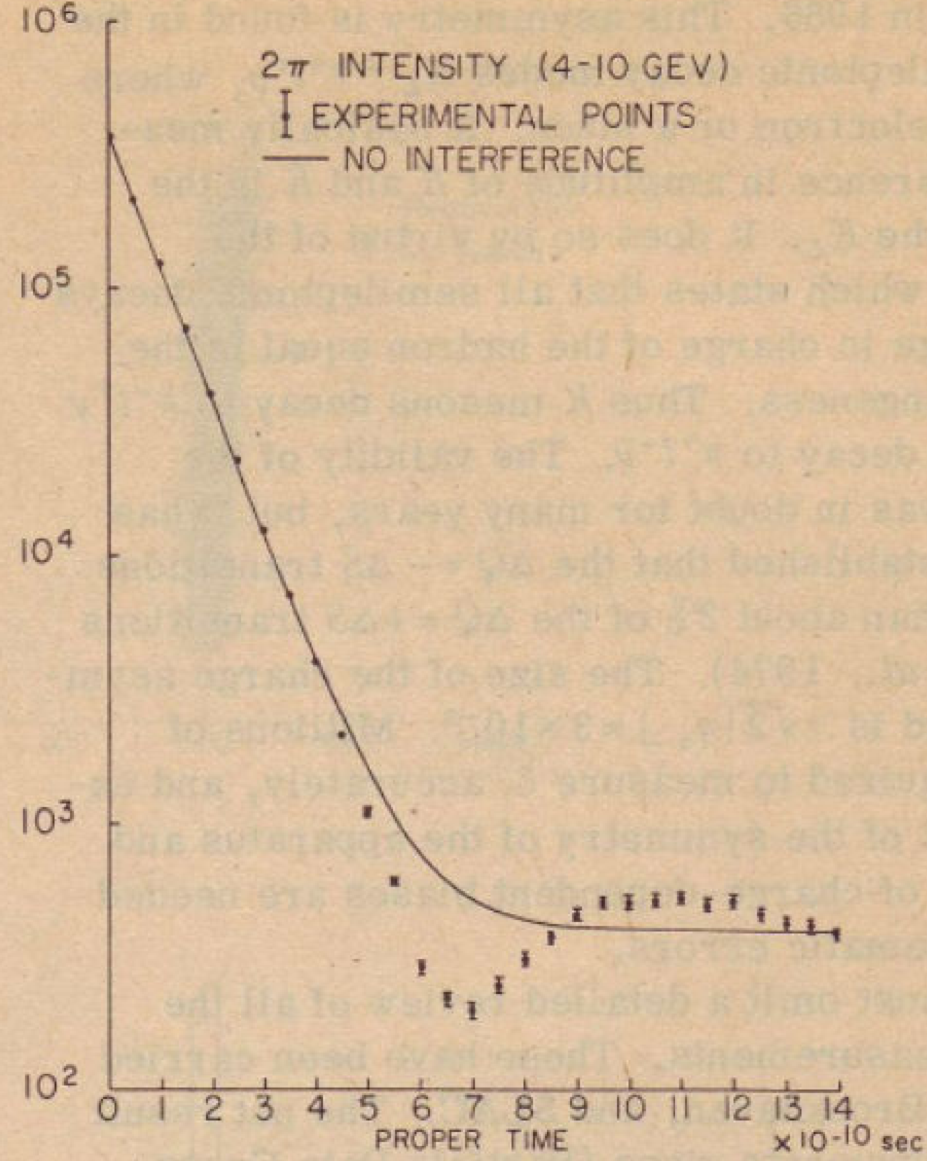


FIG. 2. Yield of $\pi^+\pi^-$ events as a function of proper time downstream from an 81 cm carbon regenerator placed in a K_L beam. Figure taken from thesis of T. Modis, Columbia University (1973); a published version of this work is given by Carithers *et al*. (1975).

$$\frac{\Gamma(K_L \to \pi^+\pi^-)\,/\,\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)\,/\,\Gamma(K_S \to \pi^0\pi^0)} = \left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 \approx 1 + 6Re(\epsilon'/\epsilon).$$

$$\begin{aligned} Re(\epsilon'/\epsilon) &= [19.2 \pm 1.1(stat) \pm 1.8(syst)] \times 10^{-4} \\ &= [19.2 \pm 2.1] \times 10^{-4}. \end{aligned}$$

KTEV

$$\begin{aligned} \mathrm{Re}(\epsilon'/\epsilon) &= (14.7 \pm 1.4 \pm 0.9 \pm 1.5) \times 10^{-4} \\ &= (14.7 \pm 2.2) \times 10^{-4}. \end{aligned}$$

NA48

Violation of CP Invariance, C Asymmetry, and Baryon Asymmetry of the Universe

НАРУШЕНИЕ *CP*-ИНВАРИАНТНОСТИ, *C*-АСИММЕТРИЯ И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ

А.Д.Сахаров

A D Sakharov

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует принять, что в природе отсутствуют тела из антивещества, т.е. Вселенная асимметрична в отношении числа частиц и античастиц (*C*-асимметрия). В частности, отсутствие антибарионов и предполагаемое отсутствие неизвестных барионных нейтрино означает отличие от нуля барионного заряда (барионная асимметрия). Мы хотим указать на возможное объяснение *C*-асимметрии в горячей модели расширяющейся Вселенной (см. [1]) с привлечением эффектов нарушения *CP*-инвариантности (см. [2]). Для объяснения барионной асимметрии дополнительно предполагаем приближенный характер закона сохранения барионов.

Принимаем, что законы сохранения барионов и мюонов не являются абсолютными и должны быть объединены в закон сохранения "комбинированного" барион-мюонного заряда $n_K = 3n_B - n_\mu$. Положено:

Letters: Journal of Experimental and Theoretical Physics Jan 1, 1967

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

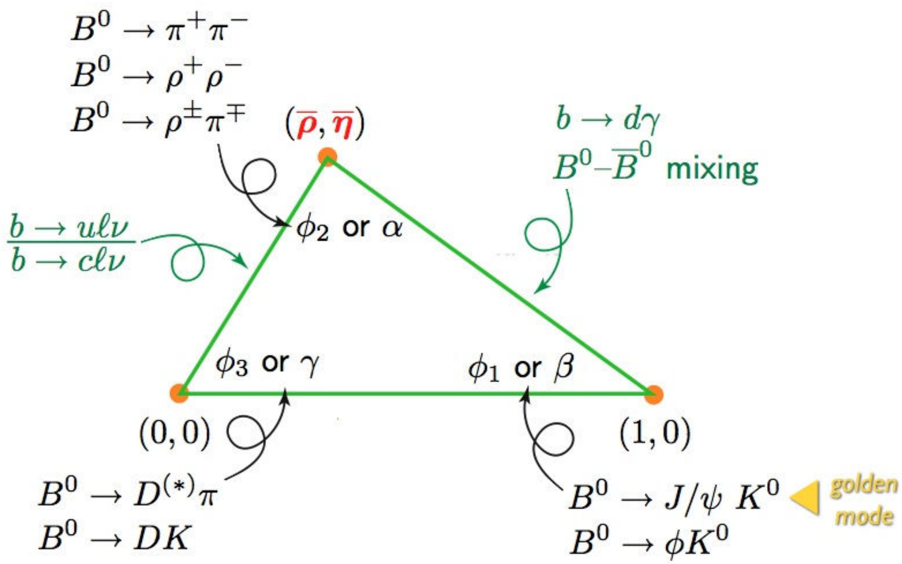
Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

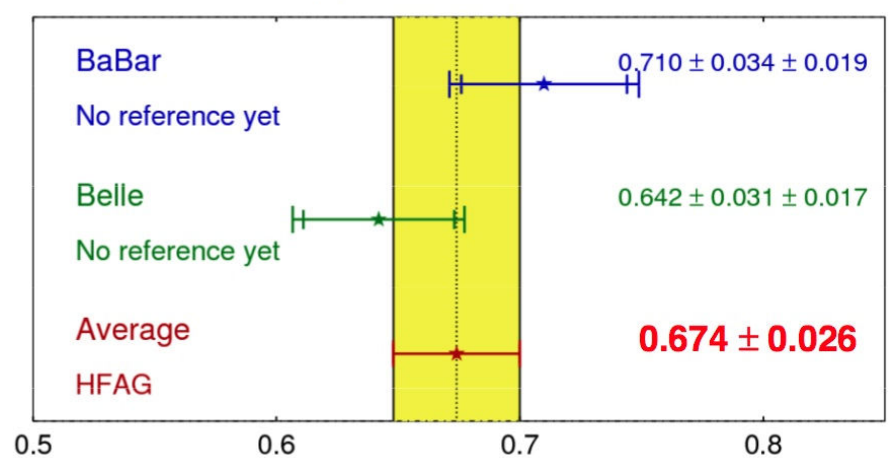
In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}.$$

The angles and sides of the unitarity triangle can be measured independently using various *B* decays.



$\sin 2\phi_1$: *BaBar* + *Belle*



END