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The Experimental Discovery of CP Violation

James W. Cronin

Abstract [This address was presented by James W. Cronin as the Nishina Memorial Lecture at the University of Tokyo, and at Yukawa Institute for Theoretical Physics in September, 1993.] The discovery of CP violation was a complete surprise to the experimentalists that found it as well as to the physics community at large. This small effect means that the symmetry means that the symmetry between the behavior of matter and antimatter is not exact. The experiment that made the discovery was not motivated by the idea that such a violation might exist. I will describe in some detail how it came to be performed in the context of of the fast moving pace of particle physics in 1963. I will review how we actually did the experiment using extracts from personal notebooks. I will discuss some difficulties we had with the apparatus and the anxiety some of us had to be sure we were correct. Such considerations are rarely revealed in a formal publication but are the realities of doing science. I will then discuss the aftermath of the experiment and the great efforts that continue to this day to understand the origin of the CP violation, which remains a mystery. The search for the origin of CP violation motivates many of the proposals for new particle facilities.

Introduction

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I am honored to be invited to Japan to give the Nishina Memorial Lecture. Yoshio Nishina was instrumental in introducing modern physics to Japan, name is also familiar to all of our students at the University of Chicago who required to repeat the Compton effect in their experimental course. In doing they compare their results with the famous

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Klein-Nishina formula which was of the earliest calculations in quantum electrodynamics [1].

I am pleased to have this opportunity to recall the discovery of CP violation. It has forced me to go back and look at old notebooks and records. It amazes me that they are rather disorganized and very rarely are there any dates on them. Perhaps this is because I was not in any sense aware the verge of an unanticipated discovery. In the second reference [2] some of the discovery. I give a list of literature on this subject which provides different perspectives on the discovery. I will begin with a review of some of the important background which is necessary to place the discovery of CP violation in proper context.

Precursors

The story begins with the absolutely magnificent paper of Gell-Mann and Pais published in early 1955 [3]. By chance I was a witness to the birth of this paper. In the spring of 1954 Murray Gell-Mann was lecturing to a small class at the University of Chicago on his scheme for organizing the newly discovered elementary particles [4]. Simultaneously Nakano and Nishijima were proposing similar ideas [5]. Among the students in this class was Enrico Fermi. As Gell-Mann was going through his scheme he mentioned that the neutral θ^0 meson was distinct from its antiparticle $\bar{\theta}^0$ because of a postulated strangeness quantum number which was conserved in strong interactions. The decay of the θ^0 and $\bar{\theta}^0$ was by weak interaction to two pions. Fermi asked, "How can θ^0 and $\bar{\theta}^0$ be distinct if they have a common decay mode." Gell-Mann did not have a ready response but the comment surely remained on his mind, for in the fall of 1954 he wrote the famous paper with Pais on the particle mixture phenomenon in the θ^0 - $\bar{\theta}^0$ system.

They gave the paper a very formal title, "Behavior of Neutral Particles under Charge Conjugation", but they knew in the end that this was something that concerned experiment. So they provided the last paragraph which reads:

> "At any rate, the point to be emphasized is this: a neutral boson may exist which has a 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."

The reference to Fermi acknowledges his comment which was the key remark that led Gell-Mann and Pais to write this paper.

Gell-Mann and Pais pointed out pointed out that while the θ^0 and $\bar{\theta}^0$ were the appropriate states for the strong interactions, the states of definite lifetime were linear combinations:

$$\theta_1 = \frac{1}{\sqrt{2}}\left(\theta^0 + \bar{\theta}^0\right)$$

and

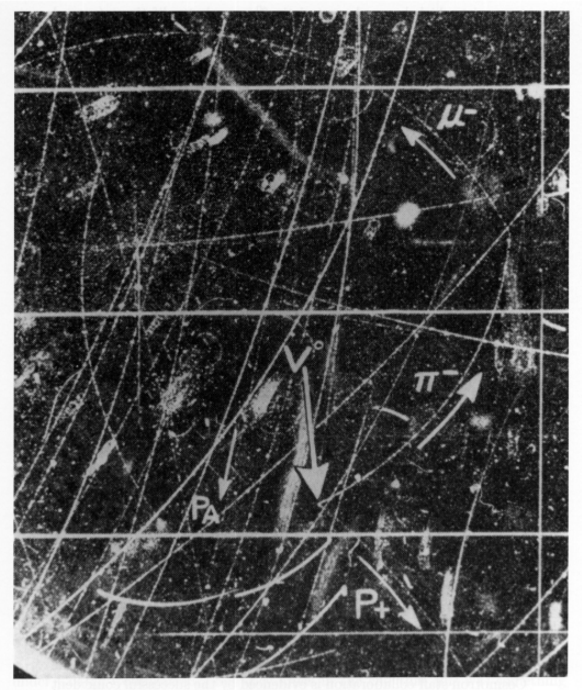

Fig. 12.1 Decay of a long-lived K meson observed in a cloud chamber at the Brookhaven Cosmotron (ref 5)

$$\theta_2 = \frac{1}{\sqrt{2}}\left(\theta^0 - \bar{\theta}^0\right)$$

These are eigenstates of the charge conjugation operator C with eigenvalues of ± 1. If C is conserved in the weak decay then one of these linear combinations is forbidden to decay to two pions and has only three body decays accessible to it (for example $\theta_2 \to \pi^- + \mu^+ \nu$). The phase space available to three bodies is less than for two so that the lifetime for the θ_2 was expected to be much longer than the θ_1.

It did not take Leon Lederman long to test the remarkable prediction of Gell-Mann and Pais. A neutral particle with a much longer lifetime than the θ^0 and no two body decay modes was predicted. With Lande, Booth, Impeduglia, and Chinowsky a successful experiment was carried out at the Brookhaven Cosmotron. Their paper entitled "Observation of Long-Lived Neutral V Particles" was published in 1956 [6]. It is interesting to read the acknowledgement in this paper.

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

Figure 12.1 shows an event in the cloud chamber which was located in a corn crib out in the back yard of the Cosmotron. The event shows manifestly a three body decay because both charged decay tracks emerge on the same side of the beam. A third neutral particle is required to balance the transverse momentum. By 1961 the combined world data showed that the upper limit for two body decays was 0.3 % of all decays [7].

The paper of Gell-Mann and Pais used conservation of charge conjugation to argue for the necessity of a long-lived neutral K meson. (After 1957 the name θ had been replaced by K.) With the discovery of parity violation the conclusion was unaltered when the charge conjugation conservation was replaced by the combined conservation of charge conjugation and parity (CP) [8]. The consequence was that the long-lived neutral K meson (K_2) was forbidden to decay to two pions.

There was another important consequence, the phenomenon of regeneration, which was described in a paper entitled, "Note on the Decay and Absorption of the θ^0" by Pais and Piccioni [9]. This paper deduced one of the beautiful aspects of the particle mixture theory. Neutral K mesons displayed in passing through matter a behavior very similar to light passing through a birefringent material. When a K_2 passes through matter the positive and negative strangeness components are attenuated by different amounts. On emerging from the matter the balance between the positive and negative components is altered so that there is a superposition of K_2 and short-lived K mesons (K_1). The K_1's decay to two pions immediately beyond the absorbing material.

Oreste Piccioni, with colleagues at the Berkeley Bevatron, demonstrated this phenomenon experimentally in a propane filled bubble chamber [10]. The introduction to their paper pays tribute to the theory of Gell-Mann and Pais.

> "It is by no means certain that, if the complex ensemble of phenomenon concerning the neutral K mesons were known without the benefit of the Gell-Mann - Pais theory, 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."

After regeneration had been established, Adair, Chinowsky and collaborators placed a hydrogen bubble chamber in a neutral beam at the Brookhaven Cosmotron to study the effect in hydrogen [11]. Figure 12.2 shows their result.
In this experiment, as in subsequent ones, the vector momenta of the two charged tracks in the decay are measured. Assuming each track is a pion, the direction and mass of a parent particle is calculated. Two body decays of K mesons will produce a peak in the forward direction at 498 MeV. The three body decays will produce a background that can be estimated by Monte Carlo and extrapolation. The forward regenerated peak was found to be too large by a factor of 10 to 20.

Adair gave a very creative explanation; he postulated a fifth force which was very weak but had a long range and hence had a small total cross section with a large forward amplitude. It also differentiated between positive and negative strangeness producing a strong regeneration. If confirmed this would have been a major discovery.

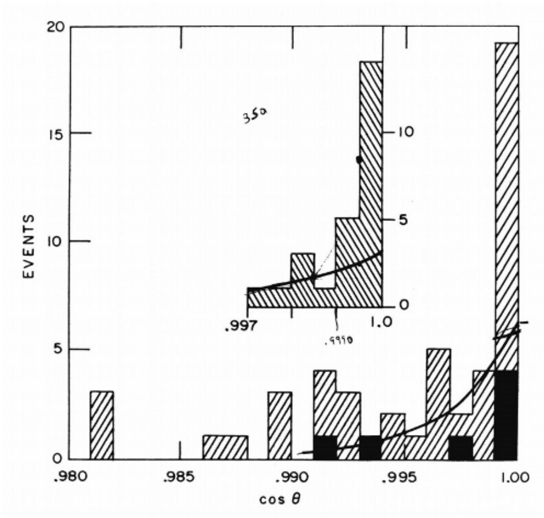

Fig. 12.2 Anomalous regeneration in hydrogen (ref 10) "Angular distribution of events which have a 2π-decay Q-value consistent with K_1^0 decay, and a momentum consistent with the beam momentum. All events are plotted for which 180 MeV $\leq$ Q $\leq$ 270 MeV, p $\geq$800 MeV/c. The black histogram presents those events in front of the thin window. The solid curve represents the contribution from K_2^0 decays"

The Experiment

At this time both Val Fitch and I were working at experiments. Val had spent much of his career working Brookhaven on separate with K mesons and was steeped in the lore of these particles which had already revealed so much about nature. Val was one of the first to measure the individual lifetimes of the various decay modes of the charged K mesons. To avoid trouble with parity one thought that the two pion and three pion decay modes were actually due to different particles [12]. On the occasion of Panofsky's visit to Brookhaven he and Val detected the K_2 mesons by electronic means [13].

The Adair experiment appeared in preprint form while Val was just finishing an experiment on the pion form factor at the AGS and I was just finishing an experiment on the production of p mesons at the Cosmotron. At the heart of this experiment was a spark chamber spectrometer designed to detect p mesons produced in hydrogen at low transverse momentum [14]. My development of spark chambers for use at accelerators was a direct consequence of the work of Fukui and Miyamoto on the "discharge chamber" [15]. At that time optical spark chambers were a new tool in which one could, by selective electronic trigger, record the trajectories of the desired events out of a very high rate background [16]. The spectrometer was state of the art at the time [17].

Val, so experienced with K mesons, came to me and suggested that together we use our spectrometer to look for Adair's anomalous regeneration. Progress in physics thrives on good ideas. I enthusiastically agreed with Val's suggestion. Jim Christenson, a Ph. D. student, and Réne Turlay, who was visiting from Prance, joined Val and me on the experiment. In addition to checking the Adair effect, it was an opportunity to make other measurements on K_2 with much greater precision.

The spectrometer I had built with Alan Clark, Jim Christenson, and René Turlay was ideally suited for the job. It was designed to look at pairs of particle with small transverse momentum. This was just the property needed to detect two body decays in a neutral beam. We also had a 4-foot long hydrogen target which would be a perfect regenerator.

The spectrometer consisted of two normal $18'' \times 36''$ beam-line magnets turned on end so that the deflections were in the vertical plane. The angle between the two magnets was adjustable. Spark chambers before and after the magnet permitted the measurement of the vector momentum of a charged particle in each arm of the spectrometer. The spark chambers were triggered by a coincidence of scintillators and a water Čerenkov counter behind each spectrometer arm. This apparatus could accumulate data much more rapidly than the bubble chamber and had a mass resolution which was five times better.

Another fortunate fact was that we had an analysis system ready to measure the spark chamber photographs quickly. We had homemade projectors and measured, instead of points, only angles of tracks and fiducials. The angular measurement was made with a Datex encoder attached to an IBM Model 526 card punch. The least count of the angular encoder was 1.5 mrad. In addition we had bought a commercial high-precision bubble chamber measuring machine which would become important in the checking of our results.

It should be noted that our support came from the Office of Naval Research. It was only later that the military stopped supporting fundamental research.

We looked around for a neutral beam at both the Cosmotron and the AGS. The most suitable beam was one used by the Illinois group [18]. The beam was directed towards the inside of the AGS ring to a narrow, crowded area squeezed between the shielding of the machine and the wall of the experimental hall. The area was dubbed "Inner Mongolia" by Ken Green one of the builders of the AGS. This area was mostly relegated to parasitic experiments working off the same target that produced the high energy small angle beams for the major experiments. The beam was produced on an internal target at an angle of 30°.

Figure 12.3 is a sketch of the setup that I placed in my notebook when we were planning the experiment. An angle of 22° between the neutral beam and each arm of the spectrometer matched the mean opening angle of $K_2^0 \to \pi^+ + \pi^-$ decays at 1.1 GeV/c which was at the peak of the spectrum at 30°. It also allowed room for the neutral beam to pass between the front spark chamber of each spectrometer arm. Heavily outlined is the decay region used for the Monte Carlo estimates of the rates. Fainter lines show the outline of the hydrogen target.

Our proposal was only two pages. It is reproduced in an Appendix. The first page describes essentially what we wanted to do. It reads in part:

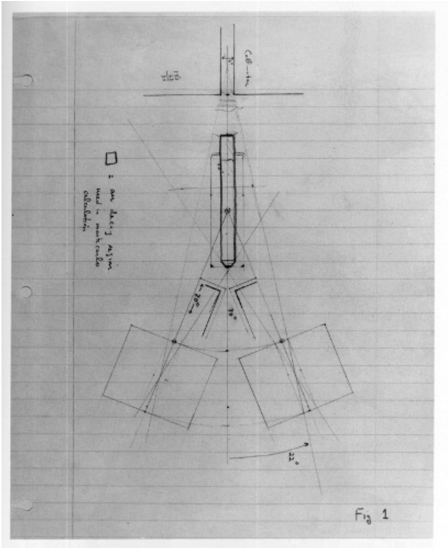

Fig. 12.3 Sketch of the spectrometer arrangement from notebook of J.W. Cronin

> "It is the purpose of this experiment to check these results with a precision far transcending the previous experiment. Other results to be obtained will be a new and much better limit for the partial rate of $K_2^0 \to \pi^+ + \pi^-, \ldots$"

One notes that we referred to a limit; we had no expectation that we would find a signal. We also proposed to measure a limit on neutral currents and study coherent regeneration. On the second page of the proposal one reads:

> "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 we 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."

This estimate turned out to be somewhat optimistic. We moved the spectrometer from the Cosmotron to the AGS in May 1963. It just barely fit inside the building. We began running in early June. There was no air conditioned trailer. The electronics, all home-made, was just out on the floor in the summer's heat. Figure 12.4 shows the only photograph that we have of the apparatus. Most prominent are the plywood enclosures which contained the optics for the photography of the spark chambers. One can discern the two magnets set at 22° to the neutral beam. Also visible are the few racks of electronics. The individual in the picture is Wayne Vernon, a graduate student, who did his thesis with Val on a subsequent experiment.

Figure 12.5 shows schematically the experimental arrangement for the CP invariance run. A large helium bag was placed in the decay region. By the time we were ready to begin the CP run on June 20, 1963 we had a better number for the flux of K_2's in the beam. The observed yield of K_2 in the beam turned out to be about

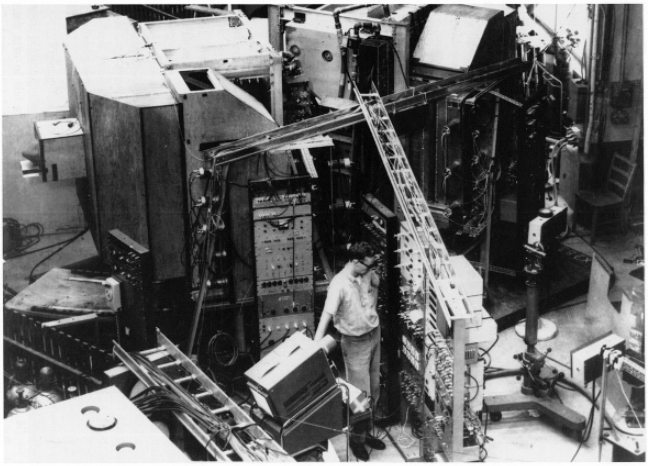

Fig. 12.4 The only existing photograph of the apparatus set up in the 30° neutral beam at the Brookhaven AGS

one-third of the original estimate given in the proposal. The best monitor was a thin scintillation telescope placed in the neutral beam upstream of the decay region which counted neutrons. Figure 12.6 is taken from my notebook. I estimated that there were $10^6 K_2$ per neutron count (in units of 10^5). The Monte Carlo efficiency to detect a $K \rightarrow 2\pi$ decay was 1.5×10^{-5}. Thus to set a limit of the order of 10^{-4}, 666 neutron counts were needed. For safety I suggested 1200 neutron counts.

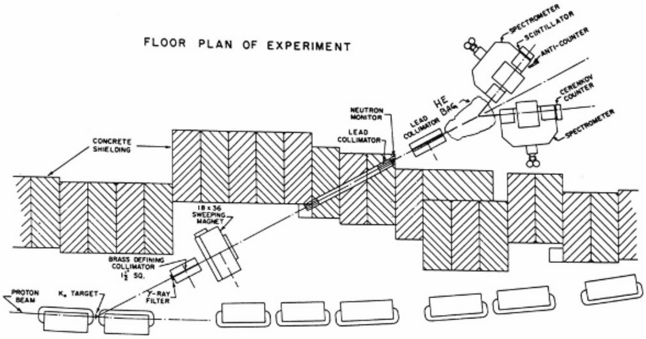

Fig. 12.5 (a) Schematic view of the arrangement for the CP run

The page of our data book from the day that the CP run began is shown in Fig. 12.7. Only ten minutes into the run one finds the note:

> "Stopped run because neutron monitor was not counting - found anti and collector transistors blown in coin. circuit - replaced - A.O.K."

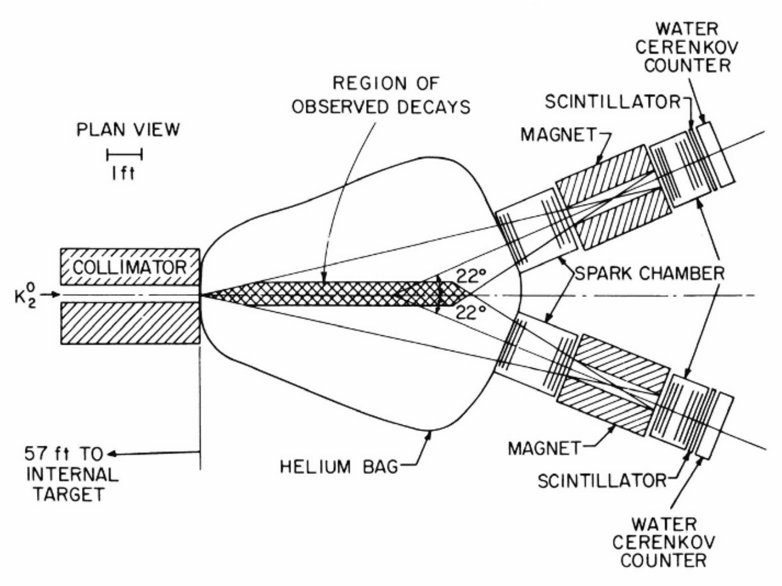

Fig. 12.5 (b) Detail of the spectrometer

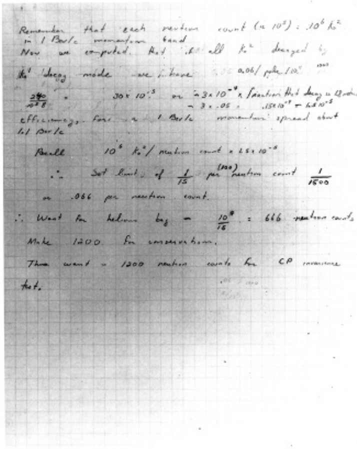
Remember that each neutron count
in 1 Bev/c momentum band
Recall
∴ Set limit of $\frac{1}{15}$ per neutron count $\frac{1}{1500}$
or .066 per neutron count.
∴ Want for helium bag = $\frac{10^4}{15}$ = 666 neutron counts
Make 1200 for conservatism.
Then want ≈ 1200 neutron counts for CP invariance test.

Fig. 12.6 Page from notebook of J. W. Cronin estimating the amount of time to set a limit of 10~4 for the branching ratio $K_2 \rightarrow \pi^+ + \pi^- / K \rightarrow all$

This was not a smooth run - it was the real world!

“3a is now meaningless - won’t write” “Film ran out sometime (?) before this - noticed it at this point - sometime before 131700 it would seem! Sorry.” “at 0445, noticed rubber diaphragm on camera lens (#3 side) was 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.”

And so it was - not smooth but working nevertheless. We ran for about 100 hours over five days. The AGS ran very well. We collected a total of more than 1800 neutron monitors, more than the 1200 we thought we needed. During about a month of running, data were taken on many aspects of K_2's including a measurement of the K_1 - K_2 mass difference and the density dependence of the coherent regeneration in copper. And, of course, a week of data was taken with the hydrogen target to search for the anomalous regeneration.

Analysis

We stopped running at the end of June and gave our first results at the Brookhaven Weak Interactions Conference in September. We reported on a new measurement of the mass difference. As I recall we did not give high priority to the CP run in the early analysis, but it was René Turlay who began to look at this part of the data in the fall. A quick look at the hydrogen regeneration did not reveal any anomaly.

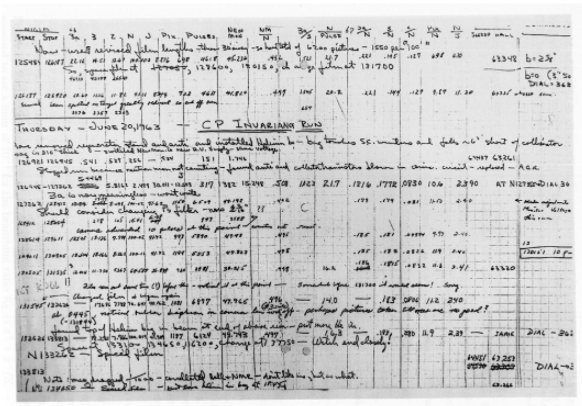

Fig. 12.7 Page from the data book at the beginning of the CP violation run, June 20,1963

All the events which were collected in the CP invariance run were measured with the angular encoder. This was complete by early 1964 and René Turlay produced the curves shown in Fig. 12.8. There were 5211 events that were measured and successfully reconstructed. The top curve shows the mass distribution of all the events assuming each charged track was a pion. Shown also is the Monte Carlo expectation for the distribution. The relative efficiency for all K_2 decay modes compared to the decay to two pions was found to be 0.23. The bottom curve shows the angular distribution of the events in the effective mass range of 490 to 510 MeV. The curve was plotted in bins of $\cos\theta = 0.0001$, presumably consistent with the angular resolution that could be obtained with the angular measuring machines. There appeared to be an excess of about 50 events expected. We then remeasured those events with $\cos\theta \geq 0.9995$ on our precision bubble chamber measuring machine.

In looking over my old notebooks I found a page which is reproduced in Fig. 12.9. When the data measured with the angular encoder were plotted in finer bins of $\cos\theta$ of .00001 the angular resolution was much better than bins of 0.0001 suggest. There was a clear forward peak and a "CP limit" of 2.3×10^{-3} was indicated at the top of the page on the basis of 42 events. Note that the mass range was from 480 to 510, larger than Fig. 12.8. The most significant statement on the page is: "To draw final conclusions we await the remeasurement on the Hydel". Hydel was the trade name of the precision bubble measuring machine.

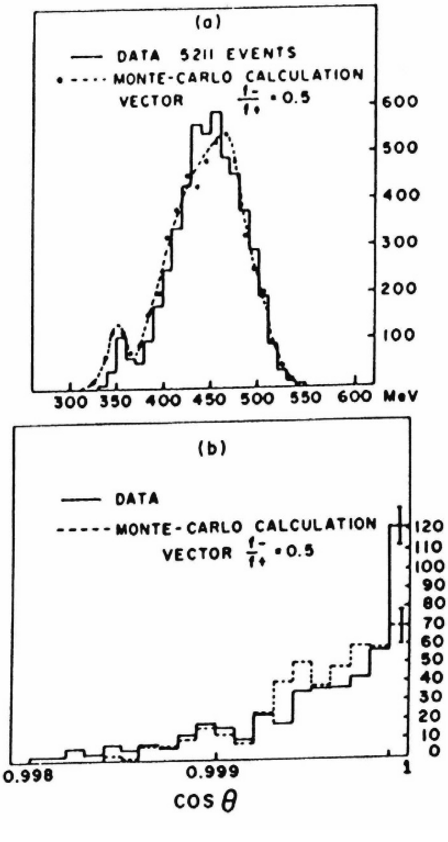

Fig. 12.8 (a) Experimental distribution in m* compared with Monte Carlo calculation. The calculated distribution is normalized to the total number of observed events, (b) Angular distribution of those events in the range 490 ≤ m* ≤ 510 MeV. The calculated curve is normalized to the number of events in the complete sample

The events were remeasured and we published the results. In our paper the key figure was the third one which is reproduced as Fig. 12.10. Here the angular distribu-

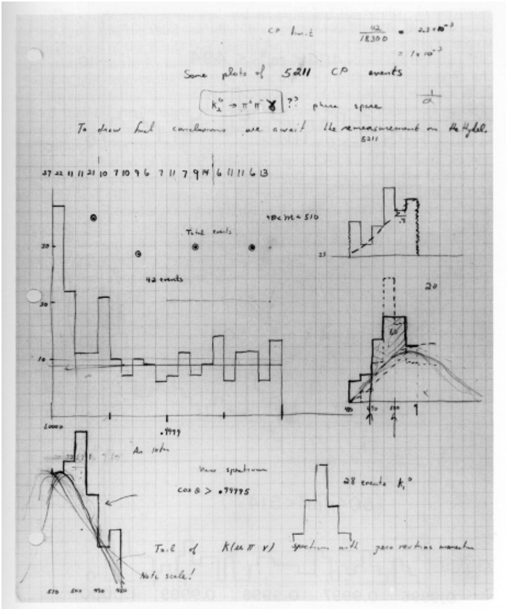

Fig. 12.9 Page from notebook of J. W. Cronin with comment on the first results of the analysis of the CP events measured with the angular encoder

tion of the events was plotted for three mass ranges with the central range centered on the K_1 mass. This was our principal evidence of the effect [19]. I found it quite convincing. Perhaps being more naive than my colleagues and not fully appreciating the profound consequences of the result, I was not at all worried that the result might be wrong. We had done an important check to be sure of the calibration of the apparatus. We had placed a tungsten block at five positions along the decay region to simulate with 2π decays of regenerated K_1's the distribution of the CP violating events. We found the mass, angular resolution and spatial distribution of the events observed with the helium bag to be identical with the regenerated K_1 events. From our own measurements of regeneration amplitudes the regeneration in the helium was many orders of magnitude too small to explain the effect. We reported a branching ratio of $(2.0 \pm 0.4) \times 10^{-3}$, a result that within the error has not changed to this day. We also reported in this paper a value of the parameter that has come to be known as η_{+-}. Wu and Yang introduced a new nomenclature which has remained [20].

The short and long lived K mesons are K_S and K_L. The parameter η_{+-} is the ratio of the amplitude, amp($K_L \to \pi^+ + \pi^-$), to the amplitude, amp($K_S \to \pi^+ + \pi^-$).

Two weeks after our publication the Illinois group published a paper entitled, “Search for CP Nonconservation in K_2^0 Decays” [21]. It reported some evidence for the two pion decay of the K_2. The data were taken in the same AGS beam at an earlier date. It was an experiment that was designed to study the form factor of the three body decays. While their experiment was not optimized for CP studies they

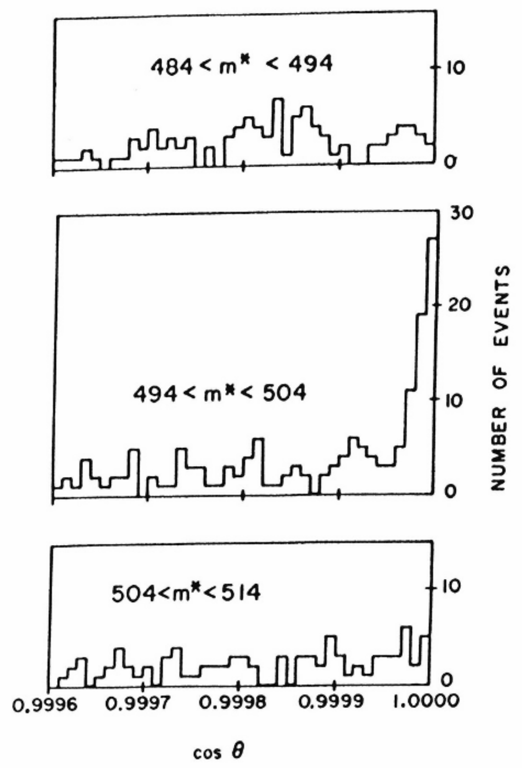

Fig. 12.10 Angular distribution in three mass ranges for events with $\cos\theta \geq 0.9995$

reported some ten events in a mass range of 500 Mev to 510 MeV which were consistent with two body decays. One important aspect was the fact that in the Illinois apparatus the decay products passed through some material. Two of the events in the forward peak showed one of the decay products interacting in material. This identified the decay products as strongly interacting.

At the time of the discovery there were all kinds of ideas brought forth to save the concept of CP violation. Among these theories were situations where the apparent pions in the CP violation would not be coherent with the pions of a K_1 decay. Thus it was important to first establish the coherence of the CP violating decays. There was an experiment carried out by Val Fitch and his collaborators [22] which has not received the proper attention of those who have reviewed the field. In this experiment Val showed explicitly that there was constructive interference between regenerated K_1 decays and the CP violating decays. The idea was clever and grew out of our extensive experience with the regeneration phenomenon. A long low density regenerator, made of thin sheets of beryllium, was prepared with a regeneration amplitude which just matched the CP amplitude. The experiment showed definitively that there was maximal constructive interference, and strengthened the idea

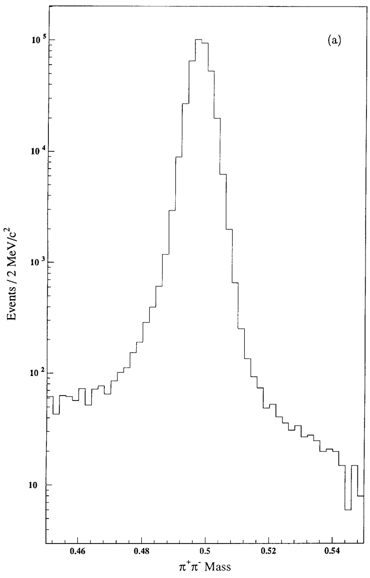

Fig. 12.11

that in the constitution of the long-lived K there was a small admixture of CP-even state in what is predominately CP-odd state.

A second important measurement was the observation of a 0.3% difference in the decay rates $K_L \to \pi^- + e^+ + \nu$ and $K_L \to \pi^+ + e^- + \bar{\nu}$ [23]. This experiment showed explicitly the asymmetry between matter and antimatter that CP violation implies.

Progress Since the Discovery

Since the discovery of CP violation there has been an enormous amount of work both on the neutral K meson system and on searches for time reversal violation in many systems. So far no effects have been found outside the neutral K meson system. Technological improvements over the last 29 years have permitted very sensitive experiments on the CP violating parameters of the K meson system. Routinely, event samples containing millions of CP violating decays in both neutral and charged modes have been obtained. The mass plots for both the neutral and charged CP violating decays from a recently reported Fermilab experiment [25] are presented in Figure 12.12. Not only does one marvel at the large number of events but other details as well. For example the plot for $K_L \to \pi^+ + \pi^-$ shows a tail towards lower mass while its neutral counterpart does not. This tail is due to the inner bremstrahlung, $K_L \to \pi^+ + \pi^- + \gamma$ which cannot occur in the neutral decay mode.

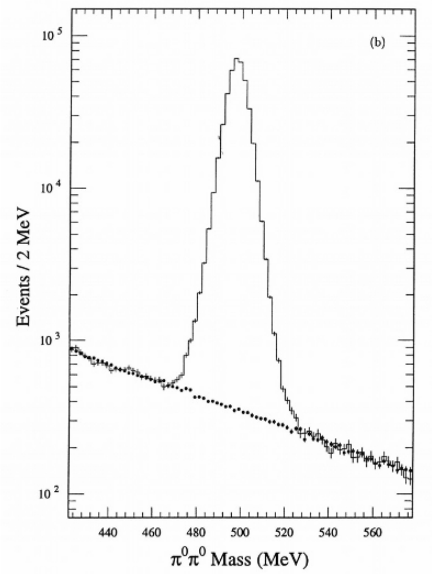

Fig. 12.12 Mass plots from a recently published Fermilab experiment ([23]). (a) $K_L \to \pi^+ + \pi^-$; (b)$K_L \to \pi^0 + \pi^0$

In recent years great there has been emphasis on the measurement of the relative strength of the CP violation in the decay to neutral pions compared to charged pions. These are characterized by the amplitude ratios η_{00} and η_{+-} respectively. An observed difference in η_{00} and η_{+-} means that there is a second independent CP violating parameter. The Number of possible theories for the origin of CP violation would be reduced, in particular the superweak theory of Wolfenstein would be ruled out [24]. This difference is usually expressed by a small quantity:

$$|\epsilon'/\epsilon| = \frac{1}{6}\left(1 - |\eta_{00}|^2/|\eta_{+-}|^2\right). \qquad (12.1)$$

A non-zero value of this quantity would indicate a "direct" CP violation and represent real progress in understanding CP violation. A recent high precision experiment at Fermilab [25] has reported $|\epsilon'/\epsilon|$ =(7.4±5.9)×10^{-4}. An experiment of comparable precision at CERN [26] has a preliminary value of $(23 \pm 7)\times10^{-4}$. While it appears that the value of $|\epsilon'/\epsilon|$ is larger than zero, both laboratories are planning more sensitive experiments to confirm this conclusion.

The most attractive "explanation" for CP violation lies in the innovative ideas of Cabbibo [27], and Kobayashi, and Maskawa [28]. The paper of Kobayashi and Maskawa is remarkable in that it postulated a third family of quarks which was required in order to have a CP violating phase. This was done at a time when there was only evidence for an up, down, and strange quark! The weak decays of the quarks are described by a 3×3 CKM matrix. The most recent theoretical calculations which include all the experimental constraints on the CKM matrix suggest a positive value for ϵ'/ϵ in the range from (1 to 30)$\times 10^{-4}$ which is compatible with the present experimental result [29].

The constraints imposed by the neutral K meson system on the CP violating phase in the the CKM matrix lead to the prediction of large CP violating effects in some of the rare decay modes in the neutral B meson system. High luminosity e^+e^- colliders (B factories) have been proposed at Cornell University and SLAC in the United States and at KEK in Japan to observe these effects [30]. It will be necessary to observe these CP violating effects in the B mesons to be certain that the origin of CP violation really rests in a phase in the CKM matrix.

CP violation is concerned with the most fundamental aspects of space and time. It is no surprise, then, that this small effect stimulated a closer relation between cosmology and particle physics. Sakharov [31] in 1967, very early after the discovery of CP violation, pointed out a mechanism whereby the early universe, composed of equal amounts of matter and antimatter could evolve to a matter dominated universe with a baryon to photon ratio of $\sim 10^{-9}$. He stated the three essential conditions: 1) Baryon nonconservation, 2) CP violation, and 3) appropriate non-equilibrium conditions related to the cooling rate of the universe and the appropriate interaction rates. This paper was far ahead of its time and received little attention. Serious consideration of the role of CP violation in the evolution to a matter dominated universe began with the paper of Yoshimura [32]. There followed a great activity which sought to understand the relation of CP violation to the evolution of the universe. It seems that the CP violation observed in the K meson system is not directly responsible for the development of a matter dominated universe [33]. Nevertheless the discovery of CP violation in the K meson system has been influential in the union of cosmology physics.

Final Remarks

I would like to conclude with some personal remarks, although I know Nature is not going to pay any attention to what I think. I would be very disappointed if the origin of CP violation only resides in a phase of the CKM matrix, which has as much or as little significance as the other constants which refer to the mixing of the quark states between the weak and the strong interactions. I would like to think that there is some more fundamental relation between the manifest CP violation in the neutral K meson system and the significant fact that our galaxy and most likely our universe is matter dominated. It may not be so. When parity violation was discovered many thought that the fact that our biological molecules show a handedness was related to the manifest handedness of the weak interaction [34]. But subsequent experiments and theoretical considerations do not support this possibility [35]. Indeed it is almost certain that the CP violation observed in the K meson system is not directly responsible for the the matter dominance of the universe, but one would wish that it is related to whatever was the mechanism that created the matter dominance.

The history of CP violation is not complete. It is gratifying to see that CP violation remains one of the major topics of research in particle physics. Let me repeat the conclusion of a previous lecture given in 1980 which remains as timely today [36].

> "We must continue to seek the origin of the CP symmetry violation by all means at our disposal. We know that improvements in detector technology and quality of accelerators will permit even more sensitive experiments in the coming decades. We are hopeful, then, that at some epoch, perhaps distant, this cryptic message will be deciphered."

Appendix

Proposal for K_2^0 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_1^0 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 $K_2^0 \to \pi^+ + \pi^-$, 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. × 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.

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