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A PARTICULAR VIEW OF PARTICLE PHYSICS IN THE FIFTIES

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In the thirties, the neutrino, the neutron, the electron and the muon were discovered. The pion and strange particles had their turn in the late forties. The fifties saw the switch from dependence on natural sources to the study of particles using accelerators. The particles and their properties were sorted out, the strange particles were systematised, the first particle resonances were found, and parity violated with a concomitant clarification of the weak interaction. It was an exciting time; the field advanced rapidly. I was young, and I played my part in this adventure. This recounting of "my" fifties is my contribution to this historical congress.

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COSMIC RAYS AND MUON DECAY

For me, particle physics started in 1947. I was a graduate student at the University of Chicago and Fermi gave a seminar on the results of the Conversi, Panchini and Piccioni experiment¹⁾, and explained that, since the negative mesotrons rapidly find their way to the atomic K shell²⁾, the observed long lifetimes were incompatible with their role as Yukawa particles. It was a beautiful and important experiment, and the explanation of Fermi was extraordinarily lucid, but also stimulating and exciting. The puzzle was at least in part cleared up a few months later when the Bristol group discovered the pion in nuclear emulsions³⁾.

Contribution to the Symposium on "Particle Physics in the 1950's, pions to quarks"

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It was a great privilege to be a student in that department at that time. There were excellent teachers: Enrico Fermi, Edward Teller, Willie Zachariasen, and Maria Meyer, to name a few. The courses of Fermi, in particular, were models of transparent and simple organization of the most important concepts. He also went to great length to show those of us who had finished the courses and were working on our Ph.D. theses, how to attack a variety of simple, general problems in different branches of physics, by gathering us together one or two evenings (I don't remember how often) a week, proposing a problem, and then, perhaps later, going through the solution.

My fellow students had also a great impact on my formation. They were a remarkable group: Yang, Lee, Goldberger, Rosenbluth, Wolfenstein, Chamberlain, Chew, Garwin and others. We worked often together on some problem, perhaps one posed by Fermi. The most impressive student-teacher of that group was Frank Yang, who had come from China after the war, and at the age of 24, despite the limited war time possibilities in China, knew all of modern physics fluently when entering graduate school in Chicago.

My thesis topic had an interesting history. Fermi asked me to look into a peculiar result⁴⁾ on stopping cosmic ray muons observed by Matt Sands, a student of Rossi. The observed rate was several times less than expected on the basis of the known cosmic ray muon flux. Part of the discrepancy could be understood in terms of an over-estimate of the acceptance of the apparatus, but a factor two was still missing. Perhaps the energy of the decay electrons was not half of the muon rest energy as the authors had assumed. At the time I was an aspiring theoretician, but Fermi suggested that I measure the energy of these electrons for my Ph.D. thesis. This was the fall of '47. By the spring of '48 the apparatus was ready. This registered the delayed coincidences between an incident meson which had stopped in an absorber and the outgoing decay electron, as function of the thickness of a second absorber. The experiment used 80 Geiger tubes and was at the time a comparatively large experiment. The results⁵⁾ showed the average decay energy to be clearly less than the 50 MeV which would be expected for a decay into an electron and a massless neutrino. Improved statistics obtained by mounting the experiment in a truck and exposing it at the top of Mt. Evans, Colorado, in the summer of '48 showed the spectrum to be continuous and, therefore, that the muon decays into an electron and two other light neutral, undetected particles, perhaps neutrinos.

This was the third process, after β decay, and muon capture, to be describable as a four fermion interaction, and Puppi⁷⁾ and Tiomno and Wheeler⁸⁾ discovered that the same coupling constant would account for all three processes. This was the birth of the idea of a universal weak interaction. The experimental result was quickly verified by Anderson and Leighton⁹⁾ and by Hinks and Pontecorvo¹⁰⁾.

ACCELERATORS AND THE PROPERTIES OF PIONS

After a postdoctoral year at the Institute of Advanced Study I came to Berkeley in the fall of '49, at the invitation of Professor Wick, to be his assistant. Once there, I was attracted by the possibilities of experimentation at the Radiation Laboratory and Gian Carlo very generously left me free to do this. Artificial mesons had only recently been seen at the 184" cyclotron¹¹⁾.

My first effort was to try to trigger the magnetic cloud chamber of Wilson Powell on stopping pions, to measure the muon decay β spectrum more precisely. I remember the kindness and hospitality with which I was accepted in Powell's lab., and also the fact that I had trouble with leaks in the little liquid scintillation counter inside the cloud chamber in which the pions were supposed to stop and decay.

This project never got off the ground. Somehow I was diverted, probably by Ed McMillan, towards looking for mesons at the 330 MeV electron synchrotron. The invention of the synchrotron focussing principle had earned Ed a Nobel Prize, and the machine was just finished and waiting for customers. There was surprisingly little interest in this new machine; the 335 MeV cyclotron had attracted the bulk of the physicists.

The external beam of the synchrotron was a Bremsstrahlung spectrum of photons; the electrons themselves could not be extracted. The detector consisted of three anthracene scintillation counters, each about two inches square and half an inch thick, with a variable thickness of absorber in between them which determined the meson energy. The mesons which stopped in an absorber following the second counter were detected by means of a delayed coincidence in the third counter. It was an early

Fig. 1 Angular distribution for the photo production of π^+ meson by a 330 MeV Bremsstrahlung beam (Ref. 12). The upper set of points are on carbon, the lower on hydrogen. The results are in clear contradiction with the dipole production expected for scalar mesons, but compatible with those for pseudoscalar mesons.

use of scintillators, and I am much indebted to Robert Hofstadter for initiating me into this new technique. The mounting of this experiment did not take more than a few weeks. I remember soldering up the circuits myself in a few nights. The experiment enjoyed the enthusiastic support of the synchrotron operators, and above all, of Ed McMillan, who was always at hand with advice and encouragement. Only positive mesons could be detected. The hydrogen process $\gamma + p \rightarrow n + \pi^+$ was measured by comparing production in polyethylene and carbon. The angular distribution¹²⁾ (Fig. 1), the first detailed measurements for the production of mesons in any process, gave some initial insight into the meson-nucleon coupling. It was clearly in disagreement with the electric dipole distribution expected for scalar coupling, but compatible with the flat distribution expected for pseudoscalar coupling. The same apparatus, equipped with an oscilloscope for the measurement of the time delay between the pion and muon, produced a first precise pion lifetime¹³⁾, $2.60 \pm 0.12 \times 10^{-8}$ sec. (The presently accepted lifetime is $(2.603 \pm 0.002) \times 10^{-8}$ sec.)

In the winter of that year, Bjorklund, Crandall, Moyer and York¹⁴⁾ observed the photon spectrum from an internal target at the Cyclotron and found the energy and angular dependences to be very different from the expectations of any then known process, but in striking agreement with what would be expected if neutral mesons, with masses similar to the $\pi^\pm$ mesons were produced, and

Fig. 2 Apparatus used in the experiment of Ref. 15. which demonstrated the existence of the neutral pion decaying to two photons.

these decayed into photons. The technique which I had been using at the synchrotron could be easily adapted to look for the decay of a neutral meson into two photons. Observation of this decay would constitute proof of the existence of the neutral meson. In this search I was joined by Pief Panofsky, much more experienced than I, and J. Steller¹⁵⁾, a graduate student. A second counter telescope was added, 1/4 inch thick pieces of lead between the first two counters served as converter, so that two γ 's could be detected and the angle between them roughly measured. The detector is shown in Fig. 2.

After a few days of effort to reduce the background, a signal was observed, and the angular correlation⁺), Fig. 3, gave clear evidence of the two photon decay of a neutral meson of similar mass and produced with similar energies, as the charged pions previously observed.

It was an exciting year of experimentation. Particle physics was just beginning and there was a great deal that could be learned with simple means, provided, of course, that one was at Berkeley, the only place in the world in which, at that time, such experiments were possible. It came to an abrupt end on June 30th 1950, when I was asked peremptorily to "hand in my badge"⁺⁺⁾ that same day. I had not signed the loyalty oath which the regents of the University had imposed on the staff, and this displeased the Laboratory Director, Prof. E.O. Lawrence. Professor Wick was similarly treated at that time.

+) May I recall here that when we first looked for, and finally found, real γ -ray coincidences, the two telescopes were at 180° (in a straight line, perpendicular to the beam). We then arranged the angle between the telescopes to be 90° , and the signal was expected to go away. Lo and behold (see Fig 3) it was ten times bigger. It took a full day for us to understand the reason, the velocity of the produced meson. Of course it was Pief who was the first to see this.

++) AEC clearance and a badge were required then to work in the Berkeley Radiation Laboratory.

Fig. 3 Angular correlation of the two photons in π^0 decay (Ref. 15).

One of the consequences of the explosion of nuclear bombs on Hiroshima and Nagasaki in 1945 was a substantial expansion, immediately after the war, of University physics research, and in particular the construction of five cyclotron laboratories, all comparable in energy to the Berkeley machine. These were at the Harvard, Rochester, Columbia and Chicago Universities and at the

Carnegie Institute in Pittsburg, in order of increasing energy. From assistant in Berkeley I became Assistant Professor at Columbia in the fall of 1950. The 380 MeV cyclotron had already begun to function. The laboratory director was Prof. Eugene Booth; Prof. James Rainwater was responsible for the most difficult part of the cyclotron, the RF system; Gilberto Bernardini was Guru in residence; among the graduate students was Leon Lederman. The big strength of Columbia was the molecular beams laboratory of Isidor Rabi, with Willis Lamb, Polykarp Kusch who was also Department Chairman, and Charles Townes. Chien Shung Wu, who had already demonstrated the correctness of the Fermi β spectrum and in a few years would discover parity violation, was installed in the nuclear laboratory.

The cyclotron was located twenty miles north along the Hudson River, on the beautiful old Nevis estate, built by Alexander Hamilton for his son, and bequeathed to Columbia University by the DuPont family. At the time I arrived, the laboratory had a unique facility: an external meson beam. The Chicago and Carnegie cyclotrons were not yet in operation; I have forgotten why these beams were not possible in Berkeley. The mesons were produced on an internal target and momentum selected by the cyclotron magnet fringing field and a slot in the shielding. When I arrived, the cyclotron had been running for a year, but only emulsion experiments were in progress. The electronic detection techniques with which I was familiar offered new possibilities to investigate the properties of the new mesons.

In the next years we exploited these beams to determine the spins and parities of charged and neutral pions, and to study the nuclear interaction of the charged pions. The first of these experiments¹⁶⁾ measured the total cross-sections of π^- mesons, in several nuclei by a simple absorption technique. The layout is shown in Fig. 4. Another very early experiment was the

Fig. 4

Experimental layout of the first determination of pion total cross sections (Ref. 16).

measurement of the differential cross-section of the pion absorption process $\pi^+ + d \rightarrow p + p$ ¹⁷⁾. Comparison with the inverse process¹⁸⁾ allowed the definitive assignment of zero spin to the pion on the basis of detailed balance¹⁹⁾. The apparatus and results are reproduced in Figs. 5 and 6. The next series of experiments involved the use of liquid hydrogen and deuterium targets and the manufacture of liquid hydrogen. The construction of these targets was a challenge, both as concerned the design, since we had no engineering help, as well as the construction in the Columbia Physics Department shop. In these early years Alan Sachs and I made the liquid hydrogen ourselves, after reactivating a primitive and somewhat dangerous prewar hydrogen liquifier on campus which could produce about

Fig. 5

Experimental layout used in the determination of the differential cross section for the absorption of positive pions in deuterium (Ref. 17). Together with the measurements on the inverse process, Ref. 19, this determined the pion spin to be zero.

Fig. 6

Angular distributions for the three scattering processes: $\pi^+ + p \rightarrow \pi^+ + p$, $\pi^- + p \rightarrow \pi^- + p$, and $\pi^- + p \rightarrow \pi^0 + n$, $\pi^0 \rightarrow \gamma$, at 135 MeV, Anderson et al., Ref. 20.

one and a half litres per hour by compressing the hydrogen and expanding it in a Joule Thompson valve. This liquid, maybe six or seven litres at a time, we then drove (surely illegally) in our own car up the West Side Highway to Nevis. In the study of the differential scattering of pions in hydrogen we were overtaken by the beautiful work of Anderson, Fermi and collaborators²⁰). Fig. 6 shows their angular distributions obtained at 135 MeV. Our own work²¹) was also quite beautiful (if I can say so) but it was restricted to lower energy by the more limited Nevis cyclotron energy. Figure 7 shows our hydrogen target, and Fig. 8 our results at 60 MeV. The crowning achievement of these scattering experiments, the discovery of the $3/2, 3/2$ resonance at ~ 180 MeV was due to Ashkin and collaborators²²) at the Carnegie cyclotron. This was possible because the energy of this machine was high enough to permit passage through resonance as shown in Fig. 9. Figure 10 shows the differential cross sections near resonance, given in a later paper²³).

Fig. 7 Liquid hydrogen and deuterium target used in a series of scattering and absorption experiments at Nevis (Ref. 21).

Fig. 8

Differential cross sections observed at 60 MeV by Bodansky et al. (Ref. 21).
 a) $\pi^+ + p \rightarrow \pi^+ + p$, b) $\pi^- + p \rightarrow \pi^- + p$, and c) $\pi^- + p \rightarrow \pi^0 + n$, $\pi^0 \rightarrow \gamma$.

Fig. 9

Excitation function of Ashkin et al. (Ref. 22), showing first hadron resonance $(3/2, 3/2)$.

Fig. 10

Angular distributions at the $3/2, 3/2$ resonance of Ashkin et al. (Ref. 23).

Fig. 11

Angular correlation of the two neutrons in the capture reaction $\pi^- + d \rightarrow n + n$, used to argue the relative parity of the charged pion and nucleon (Ref. 24).

Another experiment characteristic of our work on the properties of pions is the observation of the capture reaction of π^- in deuterium: $\pi^- + d \rightarrow n + n$.²⁴⁾ The reaction had been surmised²⁵⁾ on the basis of the lower yield of γ -rays in deuterium capture relative to that in hydrogen, but we set out to observe the reaction itself. The same target was used, but filled with deuterium. The two neutrons were detected and their angular correlation measured (see Fig. 11). It could be convincingly argued that the capture must proceed from the s-state²⁶⁾, and that therefore the π^- could only be pseudoscalar.

STRANGE PARTICLES

The discovery in 1947 of the "V particles" by Rochester and Butler²⁷⁾ did not immediately declench a great deal of activity in the States, although in Europe important cosmic ray results, obtained in emulsions and cloud chambers, continued to appear. I remember in 1949, on a bulletin

board of the Institute for Advanced Study in Princeton, a beautiful photomicrograph of a τ^+ meson decaying into three pions, obtained in an emulsion in Powell's lab. We all saw it, but did not react. It was too difficult to accept the notion of entirely new types of particles. The field began to come alive in America only after the publication in 1950²⁸⁾ by Leighton and Anderson of a larger number (34) of cloud chamber events.

Because many new particles were being observed, the early experimental situation was most confused. I would like to recall here an incident at the 1952 Rochester Conference, in which the puzzle of the neutral V's was instantly clarified and which made a big impression on me. It was the session on the neutral V particles. Carl Anderson was in the chair, but Oppie (J. Robert Oppenheimer) was dominant. He called on his old friends, Leighton from Cal Tech and Fretter from Berkeley, to present their results, but no-one was much the wiser after that. Some in the audience, clearly better informed than I was, asked to hear from Thompson from Indiana, but Oppie did not know Thompson, and the call went unheeded. Finally there was an undeniable insistence by the audience, and, reluctantly the lanky young mid-westerner was called on. He started slowly and deliberately to describe his cloud chamber, which in fact was especially designed to have less convection than previous chambers, an improvement crucial to the quality of the measurements and the importance of the results. Oppenheimer was impatient with these details, and sallied forth from his corner to tell this unknown that we were not interested in details, that he should get on to the results. But Thompson was magnificently imperturbable: "Do you want to hear what I have to say, or not?". The audience wanted to hear, and he continued as if the great master had never been there. A few minutes later Oppie could again no longer restrain himself, and tried again, with the same effect. The young man went on, exhibited a dozen well measured V^0 's and, with a beautiful and original analysis, showed that there were two different particles, the $\Lambda^0 \rightarrow p + \pi^-$, and the $\theta^0 \rightarrow \pi^+ + \pi^-$. The θ^0 (θ for Thompson) is the present K^0 . The graph he showed us at that conference²⁹⁾ is reproduced in Fig. 12.

The first accelerator experiment on the "new unstable particles" was the one of Fowler, Shutt, Thorndyke and Whittemore³⁰⁾ at the Brookhaven National Lab. cosmotron which could produce external pion beams of up to 1.5 GeV. This experiment demonstrated the very important concept of

Fig. 12

Distribution in the $P_T - \alpha$ plot of 12 V^0 's ($\alpha = (p_+^2 - p_-^2)/p^2$) shown by Thompson at the 1952 Rochester Conference, which demonstrated that there were two different V^0 particles, the Λ^0 and θ^0 .

"associated production" which had only some months before been proposed by Gell-Mann and Pais to account for the quasi stability of the new particles. The group had developed the "diffusion chamber", a continuously sensitive cloud chamber in which super-saturated vapour is produced in a thermal gradient. The chamber was filled with 20 atm. of hydrogen gas and exposed to 1.5 GeV π^- mesons. Five cases of the associated production reaction $\pi^- + p \rightarrow \Lambda^0 + \theta^0$ were found.

Another beautiful early accelerator experiment on strange particles that I want to mention here is the experiment of Leon Lederman and friends³¹⁾, in which the long lived neutral kaon was discovered. Gell-Mann and Pais³²⁾, had noticed, in a penetrating analysis, that there should be two K^0 's, one the antiparticle of the other, that the observed θ^0 was one linear combination, and that the other combination should have a much longer life, comparable to that of the charged K particles. To this end an old but hardly used 36" cloud chamber was refurbished and put six metres from a target struck by the external proton beam³³⁾ at the cosmotron, far enough from the target so that the known V^0 's could not reach it. It was by no means easy to find the 23 V^0 events, all of which had to be three body decays, since they did not conserve transverse momentum. The observed momenta were

Fig. 13 Mass of the decaying particle as a function of assumed velocity and decay mode in the experiment of Lande et al. in which the K_L^0 was discovered (Ref. 31)

consistent with the decay of a particle of 500 MeV mass into pion, electron and neutrino (see Fig. 13).

My own participation in the study of these particles began in 1954, when three students, Jack Leitner, Nick Samios, and Mel Schwartz, and I, started to experiment with the bubble chamber, which had been invented by Don Glaser two year before. We made a 10 cm diameter propane chamber, with much advice from Don himself, but we made one non-negligible improvement: the liquid was recompressed some milliseconds after the expansion to prevent the bubbles from rising and collecting on top. This made it possible to cycle at a reasonable rate (a few times per second). Our first publication: "Properties of heavy unstable particles produced by 1.3 GeV π^- mesons" ³⁴⁾ was the first application of Glaser's invention. The chamber had grown to 15 cm diameter and is shown in Fig. 14. In a two day exposure, fifty five associated production events in hydrogen were obtained, many more than had been obtained in the previous two yeas by older techniques. Figure 15 reproduces one of these events. The paper gives evidence that the spins of Λ^0 and Σ^- hyperons are 1/2 and broaches the subject of the possible observation of parity violation in hyperon decay, some six months before the demonstration of parity violation by C.S. Wu et al. The relevant distribution is

Fig. 14

The chamber used in the first bubble chamber experiment (Ref. 34).
 (I am indebted to Bill Fowler for this figure from an extinct Nevis report.)

reproduced in Fig. 16. The up down asymmetry (the angle ϕ of the figure) is 7 ± 15 , a two standard deviation effect, but the authors (correctly) considered the statistics inadequate for such an important conclusion.

Fig. 15

Example of the reaction $\pi^- + p \rightarrow \Lambda^0 + \theta^0$, $\theta^0 \rightarrow \pi^+ + \pi^-$, $\Lambda^0 \rightarrow p + \pi^-$, in the first bubble chamber experiment, Budde et al., Ref. 34.

Fig. 16

Angular correlation in the production and decay of 22 Λ^0 's seen in the same experiment. The angle ϕ is the up-down angle. The observed up-down asymmetry of 7+15 is a two standard deviation evidence in favour of parity violation, one-half year before its discovery.

These early bubble chambers could be constructed rather fast. Less than half a year after this first publication, we submitted results³⁵⁾ from the next chamber, with eight times the volume and now in a magnetic field. It describes two events in which Σ^0 's are produced on free protons according to the reaction $\pi^- + p \rightarrow \Sigma^0 + \theta^0$ and where both the Λ^0 and the γ from the Σ^0 decay are observed. One of the events is reproduced in Fig. 17. These events demonstrated the existence of the Σ^0 and determined its mass to a few MeV. The existence of the Σ^0 was one of the first confirmations of SU_3 , which had put the Σ^+ and Σ^- into an isospin triplet together with the as yet unobserved Σ^0 .

Fig. 17

First observation of the $\Sigma^0, \Sigma^0 \rightarrow \Lambda^0 + \gamma$, by Cretien et al. (Ref. 35).

Towards the end of that year, little more than a year after our first bubble chamber publication, we published results on the angular correlation in Λ production and decay which were conclusive in showing parity violation³⁶⁾. There were now ten times the number of events, obtained mostly in the 30 cm propane chamber, but including also some events from our first liquid hydrogen chamber, also 30 cm in diameter and in the same magnet, and events as well from a Michigan group which included Don Glaser and Martin Perl! The relevant angular distribution is shown in Fig. 18⁺).

The same exposures provided also the data for an analysis³⁷⁾, based on an argument of Adair³⁸⁾, to determine the spins of the Λ^0 and Σ^- hyperon. This argument shows that near threshold,

⁺) Note that the up down angle here called θ was labelled ϕ in the previous publication (Fig. 14).

Fig. 18 Up-down angular distribution in the correlation of production plane and decay angle (the angle called θ here is the same as that called ϕ in Fig. 16). The parity violation is now statistically firm (Ref. 36).

and for forward and backward hyperon production angles, the angular correlation between incident pion and decay pion is a predictable function of the hyperon spin. The prediction for spin one half is a flat distribution, which was found to be the case for both Λ^0 and Σ^- (Fig. 19).

Fig. 19 Distribution in the angle between the incident and the decay pion in the process $\pi^- + p \rightarrow \Lambda^0 + \theta^0$ and $\pi^- + p \rightarrow \Sigma^- + K^+$ near threshold. The flat distributions observed both for a) the Λ^0 , and b) the Σ^0 , show that the spins of both hyperons are 1/2 (Ref. 37).

The 12" H_2 chamber, which provided some of the data for these last two experiments, was also exposed at the Nevis Cyclotron in a search for the rare decay $\pi^+ \rightarrow e^+ + \nu$, and in order to measure the π^0 parity. A drawing of the chamber in its magnet is shown in Fig. 20. The pion β decay search was successful³⁹; six cases were found, at a rate consistent with the prediction of μ -e universality. The results were published simultaneously with similar results from a CERN counter experiment⁴⁰. The second of these experiments⁴¹ searched for the very rare double internal conversion of π^0 decay, $\pi^0 \rightarrow 2e^+ + 2e^-$, which was theoretically expected at a rate of $\sim 2/\pi \cdot \alpha^2$. The angular correlations permit a direct test of the π^0 parity: if two pairs are chosen so that the angles between the members of a pair are the smaller of the two possible choices, then the distribution in the angle between the two planes so defined is expected to be peaked at zero degrees for scalar, and at 90° for pseudoscalar mesons. 7×10^5 pictures were taken, with approx. 10 stopping π^- in each. About half of these are

Fig. 20

Our first hydrogen chamber, 12" diameter, in a 13.4 kG field. The chamber was used for the experiments of Refs. 36, 37, 39, 41.

Fig. 21

A double internal conversion observed in the stopping and capture of π^- mesons in hydrogen: $\pi^\pm + p \rightarrow \pi^0 + n$, $\pi^0 \rightarrow 2e^+ + 2e^-$, Plano et al. (Ref. 41).

Fig. 22

Angular correlation of the two decay planes in the double internal conversion of the π^0 . The correlation is that expected for pseudoscalar mesons.

converted to 4 MeV π^0 's in the capture. 103 double internal conversion events were found, one is shown in Fig. 21. The angular correlation (Fig. 22) shows the pseudoscalar parity of the π^0 .

THE TWO NEUTRINOS EXPERIMENT

Under the two foregoing headings I have recalled some of the experiments performed at Nevis, or at the Brookhaven National Laboratory. This Columbia-BNL collaboration was very fruitful and contributed a great deal to the output of the cosmotron and the early AGS. The crowning achievement of the Columbia-BNL collaboration was probably the two neutrino experiments of '61-'62⁴²⁾, and it may be reasonable to mention it here, even though it happened after the period to which this conference is dedicated.

The experiment followed the suggestion of Bruno Pontecorvo⁴³⁾ and Mel Schwartz⁴⁴⁾ that, at the higher energy accelerators then being constructed, it should be possible to achieve neutrino "beams" from pion and kaon decay, with sufficient intensity such that neutrino reactions could be observed in multi-ton detectors. Such detectors had never been constructed. Luckily, optical multi-plate spark chambers had just been invented, and these formed the basis of the detector. The

ten modules were arranged in two storeys of five. Each consisted of nine 1" aluminium plates and had a mass of about one ton. The beam was taken at the smallest possible angle, 7.5° , from an internal target at the AGS. It had a decay length of 20 m, and a muon shield of 13.5 m of iron. The detector was protected against cosmic rays by anticoincidence counters, and was triggered by means of counter planes between the modules. After some initial skirmishes with the shield, which had to be "neutron proofed", 56 events were obtained in a run of about a month. These could be shown to be neutrino events, contaminated by about 10% stopping muons from cosmic rays and not more than 20% machine produced background.

Most of the events contained a penetrating track, presumably a muon, such as the event shown in Fig. 23. Six events were seen with irregular sparks indicating a shower, but these had fewer sparks than would be expected for electrons of the energy of the observed muons, as can be seen from Fig. 24. This established that the neutrino emitted in the dominant pion and kaon decays is

Fig. 23

Typical event observed in the neutrino experiment of Danby et al. (Ref. 42) in multiplate spark chambers. It shows a penetrating track, probably a muon, and some hadronic debris.

different from the neutrino of β decay. We had discovered that there are two neutrinos, but we did not discover neutral currents. Why not? The reason may be twofold. On the one hand, and very important, we were not looking for it; at the time no-one imagined that neutral currents exist. On the other hand, the experiment was too marginal, both systematically and statistically. Now we know neutral currents exist, but the rates are only $\sim 1/5$ of the charged current rates, and the visible energy is only one half, on the average, since the outgoing neutrino leaves no sparks. The six "shower" events referred to above may very well be neutral current events, but given our uncertainty concerning possible neutron background and neutrino background with short range muons, no positive conclusion could have been drawn.

Fig. 24

Spark distribution of the six muonless events (bottom), as well as the expected distribution (top) obtained in an auxiliary exposure to 400 MeV electrons, and normalized to the expected number of showers, assuming equal electron and muon production. The missing electrons are the evidence that the muon neutrino is distinct from the electron neutrino.

REFERENCES

- Ref. 1 M. Conversi, E. Panchini and O. Piccioni, Phys. Rev. 71 (1947) 209.
- Ref. 2 E. Fermi, E. Teller and V. Weisskopf, Phys. Rev. 71 (1947) 314.
- Ref. 3 C.M.G. Latters, G.P.S. Ochiellini, and C.F. Powell, Nature 160 (1947) 453, 486.
- Ref. 4 B. Rossi, M. Sands and R.F. Sard, Phys. Rev. 72 (1947) 120.
- Ref. 5 J. Steinberger, Phys. Rev. 74 (1948) 500.
- Ref. 6 J. Steinberger, Phys. Rev. 75 (1949) 1136.
- Ref. 7 G. Puppi, Nuovo Cimento 6 (1949) 194.
- Ref. 8 J. Tiomno and J.A. Wheeler, Rev. Mod. Phys. 21 (1949) 144.
- Ref. 9 R.B. Leighton, C.D. Anderson and A.J. Seritt, Phys. Rev. 75 (1949) 1432.
- Ref. 10 E.P. Hinks and B. Pontecorvo, Phys. Rev. 77 (1950) 102.
- Ref. 11 E. Garder and C.M.G. Lattes, Science 107 (1948) 270.
- Ref. 12 J. Steinberger and A.S. Bishop, Phys. Rev. 78 (1950) 493.
- Ref. 13 O. Chamberlain, R.F. Mozley, J. Steinberger and C. Wiegand, Phys. Rev. 79 (1950) 394.
- Ref. 14 Bjorklund, Crandell, Meyer and York, Phys. Rev. 77 (1950) 213.
- Ref. 15 J. Steinberger, W.K.H. Panofsky and J. Stellar, Phys. Rev. 79 (1950) 802.
- Ref. 16 C. Chedester, P. Isaacs, A. Sachs and J. Steinberger, Phys. Rev. 82 (1951) 958.
- Ref. 17 R. Durbin, H. Loar and J. Steinberger, Phys. Rev. 83 (1951) 646.
- Ref. 18 V.Z. Peterson, Phys. Rev. 79 (1950) 407
Cartwright, Richman, Whitehead and Wilcox, Phys. Rev. 81 (1951) 652.
- Ref. 19 R.E. Marshak, Phys. Rev. 82 (1951) 313.
- Ref. 20 H.L. Anderson, E. Fermi, R. Martin and D.E. Nagle, Phys. Rev. 91 (1953) 155.
- Ref. 21 D. Bodansky, A. Sachs and J. Steinberger, Phys. Rev. 93 (1954) 1367.
- Ref. 22 J. Ashkin, J.P. Blaser, F. Feiner, J. Gormaux and M.O. Stern, Phys. Rev. 93 (1954) 1129.
- Ref. 23 J. Ashkin, J.P. Blaser, F. Feiner and M.O. Stern, Phys. Rev. 101 (1956) 1149.
- Ref. 24 Panofsky, Ammodt and Hadley, Phys. Rev. 81 (1951) 565
- Ref. 25 K. Brueckner, R. Serber and K. Watson, Phys. Rev. 81 (1951) 57.

- Ref. 26 W. Chinowsky and J. Steinberger, Phys. Rev. 95 (1954) 1561.
- Ref. 27 G.D. Rochester and C.C. Butler, Nature 160 (1947) 855.
- Ref. 28 A.J. Seriff, R.B. Leighton, C. Hsiao, E.W. Cowan and C.D. Anderson, Phys. Rev. 78 (1950) 290.
- Ref. 29 The publication is: R.W. Thompson, A.V. Buskirk, L.R. Etter, C.J. Katzmark and R.H. Rediker, Phys. Rev. 90 (1953) 329.
- Ref. 30 W.B. Fowler, R.P. Shutt, A.M. Thorndyke and W.L. Whittemore, Phys. Rev. 93 (1954) 861.
- Ref. 31 K. Lande, E.T. Booth, J. Impeduglia, L.M. Lederman and W. Chinowsky, Phys. Rev. 103 (1956) 1901.
- Ref. 32 M. Gell-Mann and A. Pais, Phys. Rev. 97 (1955) 1387.
- Ref. 33 Piccioni, Clark, Cool and Friedlander, Rev. Sci. Instr. 26 (1955) 232.
- Ref. 34 R. Budde, M. Cretien, J. Leitner, N.P. Samios, M. Schwartz and J. Steinberger, Phys. Rev. 103 (1956) 1827.
- Ref. 35 H. Plano, N. Samios, M. Schwartz and J. Steinberger, Il Nuovo Cimento V, (1957) 216.
- Ref. 36 Eisler, Plano, Prodell, Samios, Schwartz, Steinberger, Bassi, Borelli, Puppi, Tanaka, Waloschek, Conversi, Franzini, Mannelli, Santangelo, Silvestrini, Glaser, Graves and Perl, Phys. Rev. 108 (1957) 1353.
- Ref. 37 F. Eisler, et al., Nuovo Cimento VII (1958) 222.
- Ref. 37 R. Adair, Phys. Rev. 100 (1955) 1540.
- Ref. 39 Impeduglia, Plano, Prodell, Samios, Schwartz and Steinberger, Phys. Rev. Lett. 1 (1958) 249.
- Ref. 40 Fazzini, Fidecaro, Merrison, Paul and Tollestrup, Phys. Rev. Lett. 1 (1958) 249.
- Ref. 41 Plano, Prodell, Samios, Schwartz and Steinberger, Phys. Rev. Lett. 3 (1959) 525.
- Ref. 42 Danby, Gaillard, Goulianos, Lederman, Mistry, Schwartz and Steinberger, Phys. Rev. Lett. 2 (1962) 36.
- Ref. 43 B. Pontecorvo, J. Expt. Theor. Phys. (USSR) 37 (1959) 1751.
- Ref. 44 M. Schwartz, Phys. Rev. Lett. 4 (1960) 306