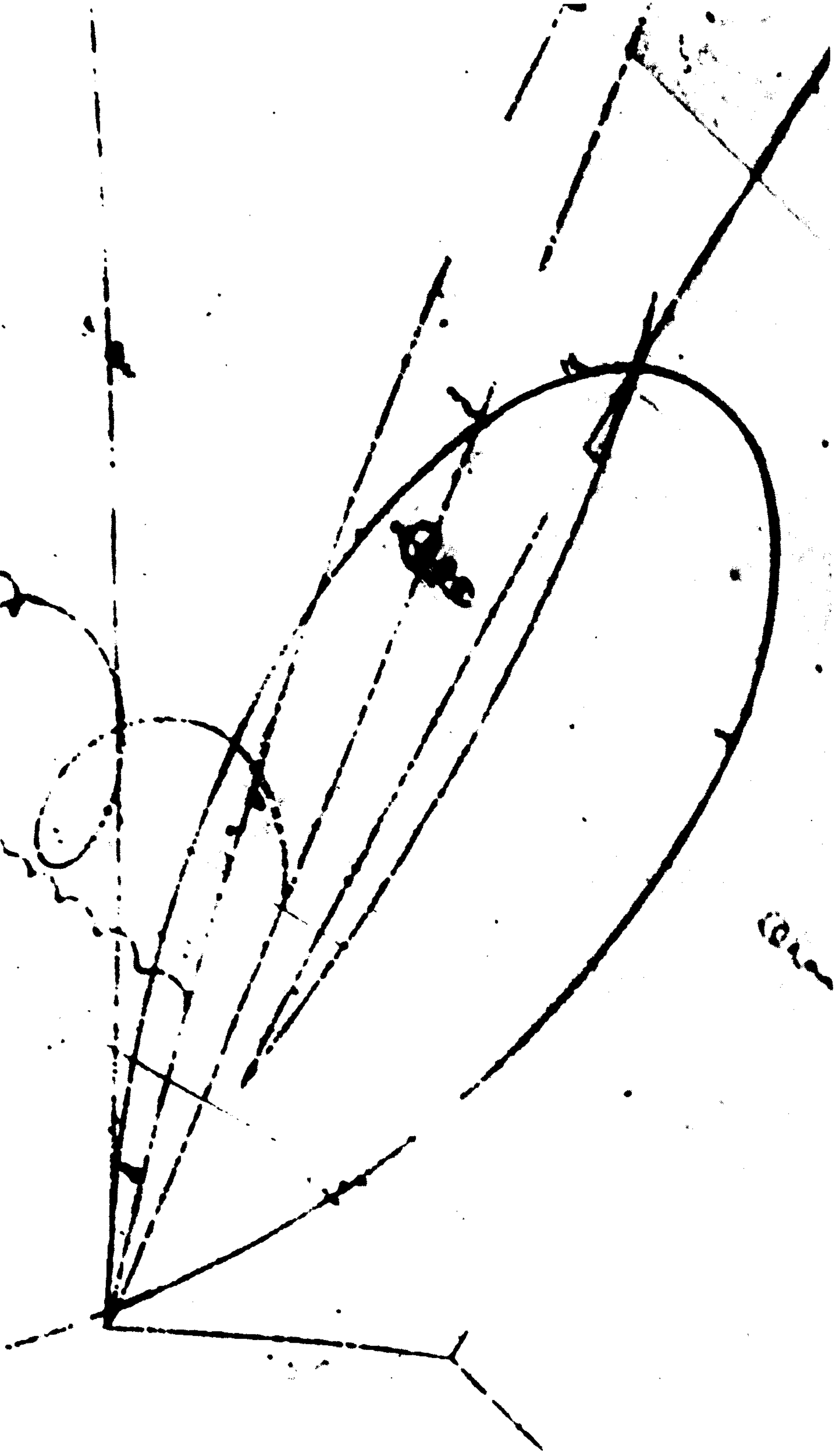
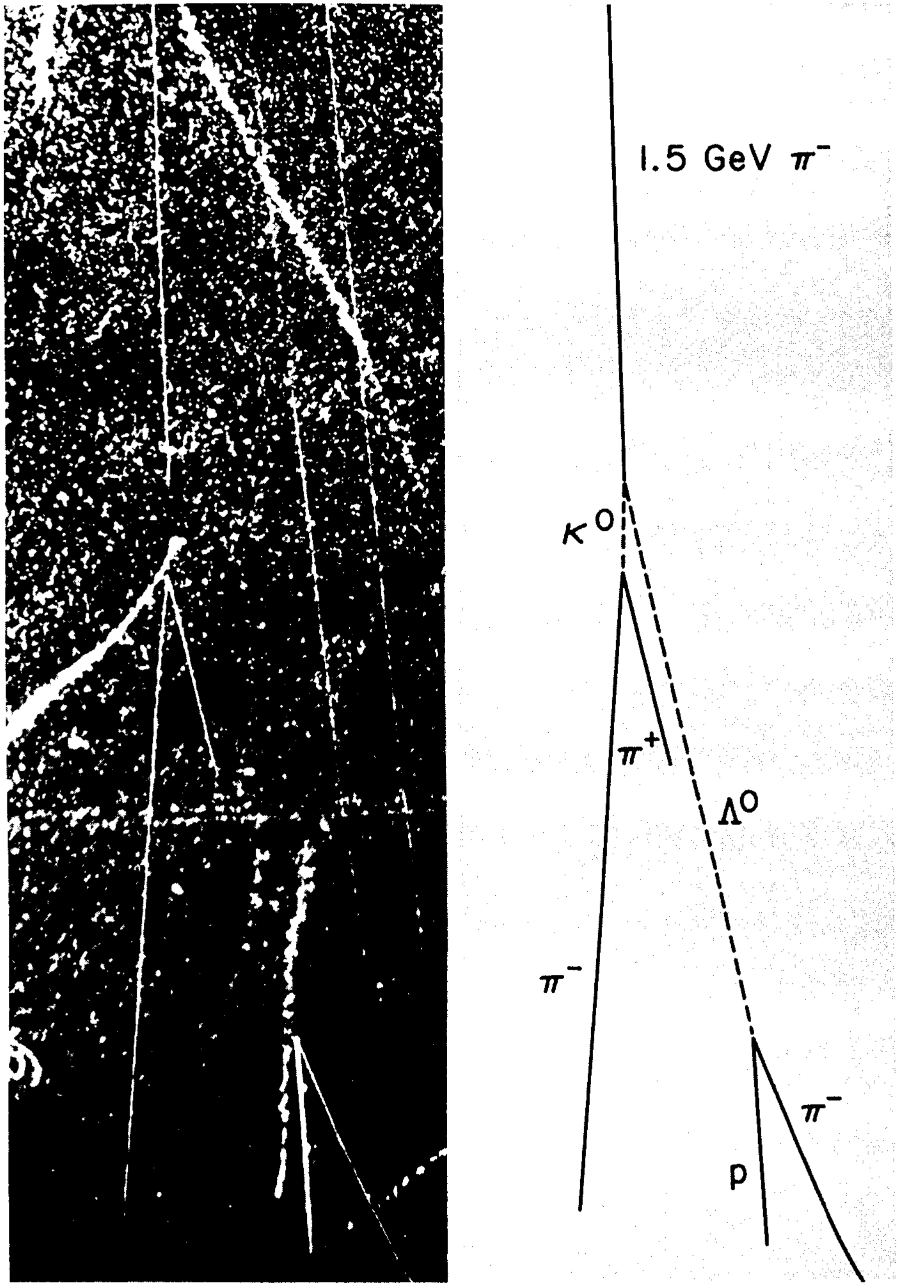


High Energy Physics Achievements at the AGS and Cosmotron...

Brookhaven National Laboratory



ASSOCIATED PRODUCTION

The discovery of V particles in cosmic ray experiments came as a surprise to physicists. "V particles" was the term used to describe a group of unstable, neutral and charged particles copiously produced in high energy collisions of other particles in cloud chambers, but amazingly long lived (10^{-10} to 10^{-8} seconds, times characteristic of decay by the weak interaction). The neutral particles left no tracks in the chamber, but often decayed into two charged particles whose tracks formed the characteristic isolated V. Since they were so readily produced in strong interactions it seemed that they should have decayed as readily through the strong interaction in times of the order of 10^{-21} seconds. Thus the decay particles would have appeared at the point of interaction of the primary particles in cloud chamber photographs of the event and of course no isolated V's would have appeared.

To explain the long lifetime, Professor Pais of the Institute for Advanced Study devised an interaction scheme using conventional field theory that would allow production of these particles through the strong interaction, but decay only through the weak interaction. However this scheme required that these particles be produced only in certain paired combinations. This was the postulate of "associated production." Professor Gell-Mann, (University of Chicago) Professor Nishijima (Osaka City University) independently carried this idea further with the introduction of a new quantum number, attributed to the V's, which is conserved in strong interactions but not in weak interactions. This quantum number was later named "strangeness."

It was generally conceded that there was no evidence in cosmic ray experiments that any of these particles must be produced in pairs. But when the Cosmotron came into operation with the ability to produce beams of 1.5 GeV pions it was possible to produce V particles artificially. The first definite evidence to support the theory of associated production came from an experiment at the Cosmotron in 1953 by BNL physicists Fowler, Shutt, Thorndike, and Whittemore. They, in collaboration with Donald Miller, developed a high pressure hydrogen-filled diffusion cloud chamber which was mounted in a magnetic field and exposed to a beam of negative pions. The combination of pions of a known energy colliding with single protons made it possible to correlate the beam pion with the V production event. In the photographs of the events they were able to identify the decay products and thus accurately calculate the masses of the parent particles. They thus concluded "the present results are consistent with the possibility of production of a V° together with one other heavy unstable particle"—the associated production process. Their next experiment showed both V°'s, one was found to be a Λ° and the other a K° ($\pi^- + p \rightarrow \Lambda^\circ + K^\circ$).

Further work at the Cosmotron by Brookhaven and university physicists indicated that V particles are produced *only* in associqted production and provided strong verification of the existence of the new strangeness quantum number which is now fundamental to our understanding of particle physics.

One of the first events observed by the BNL group showing both V particles (a K° and a Λ°) produced in associated production. The trajectories of the K° and Λ° are indicated by dashed lines in the sketch, since neutral particles leave no tracks in the cloud chamber.

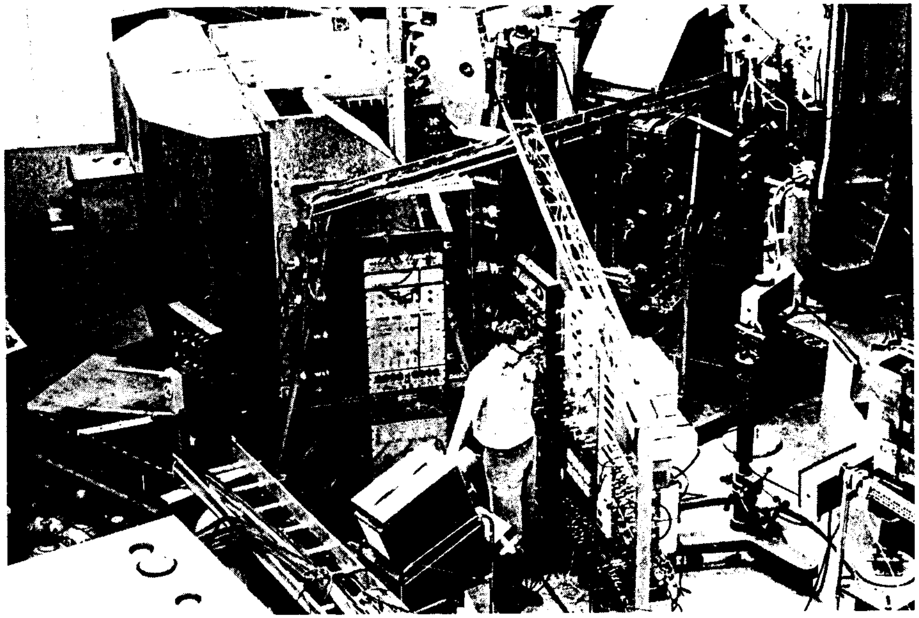
DISCOVERY OF A CP VIOLATION

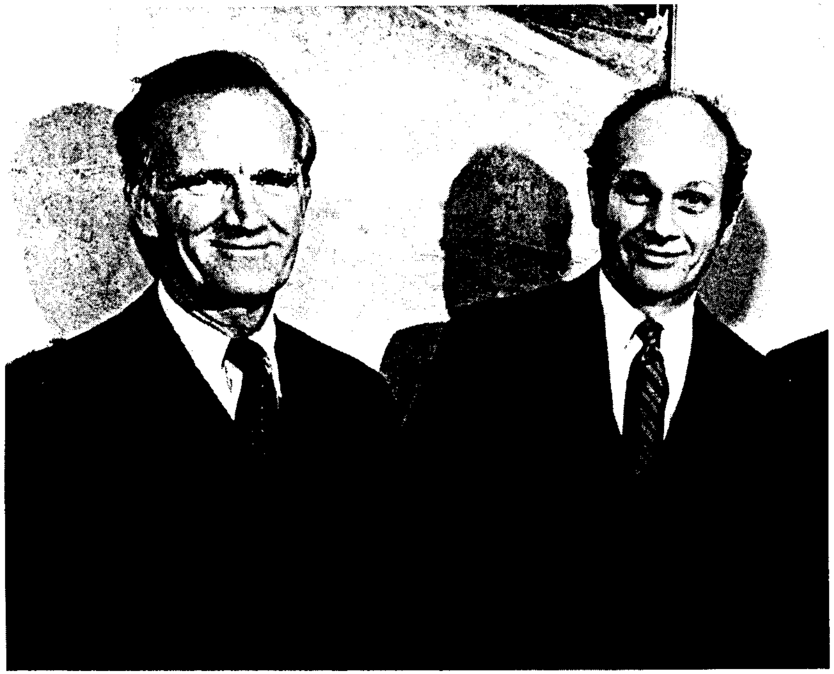
A Princeton group headed by Professors Cronin and Fitch working at the AGS in 1963 had set up an experiment to study the characteristics of K_2° decays including "a new and much better limit for the partial rate of $K_2^{\circ} \rightarrow \pi^+ + \pi^-$." The 2π decay mode of the K_2° was forbidden by the rule of CP invariance which holds that the operation of interchanging matter with antimatter combined with a mirror reflection leaves any physical system unchanged. A violation of this rule is profound since it implies space is not completely symmetrical.

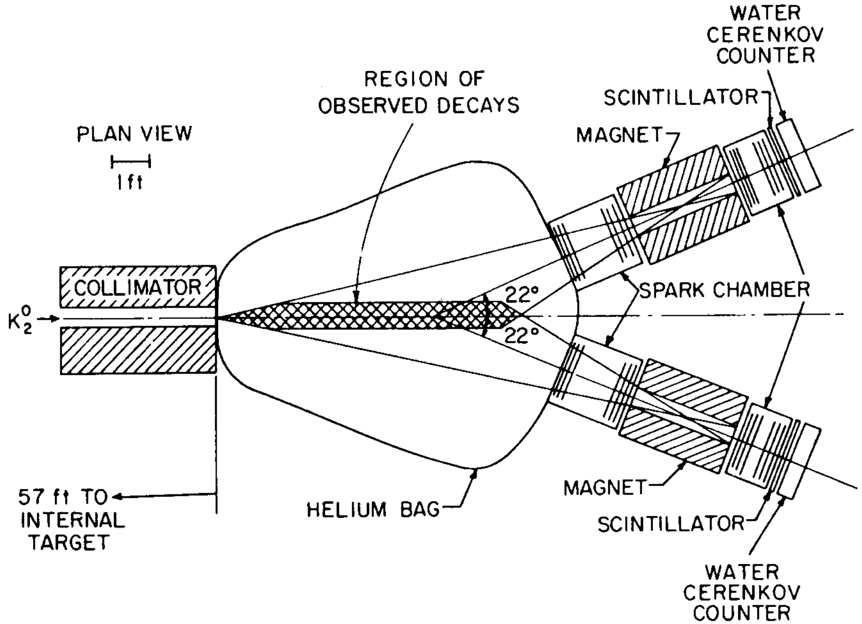
The experiment instead of setting a new low limit on the probability of this decay mode, actually showed that the K_2° did sometimes decay into a π^+ meson and a π^- meson. This is generally considered the most important experimental discovery in weak interaction physics and resulted in Professors Cronin and Fitch being awarded the Nobel Prize in 1980.

The violation observed is quite small (the decay is a rare one, ~0.2%), but it was confirmed by a number of other experiments. Up to now there is no satisfactory theory of the origin of the violation in spite of intensive experimental and theoretical work.

Further as a consequence of one of the most basic theorems of particle physics —CPT invariance — if CP invariance is violated then T invariance is also violated. Thus this experiment is evidence that the direction of time influences the laws of physics —contradicting another fundamental theorem of particle physics.







Nobel Laureates Fitch and Cronin at the BNL celebration of the award.

A photograph and sketch of the apparatus used in the discovery of the CP violation. A scientist is checking the electronics of the event detection system.

DISCOVERY OF A NEW KIND OF NEUTRINO

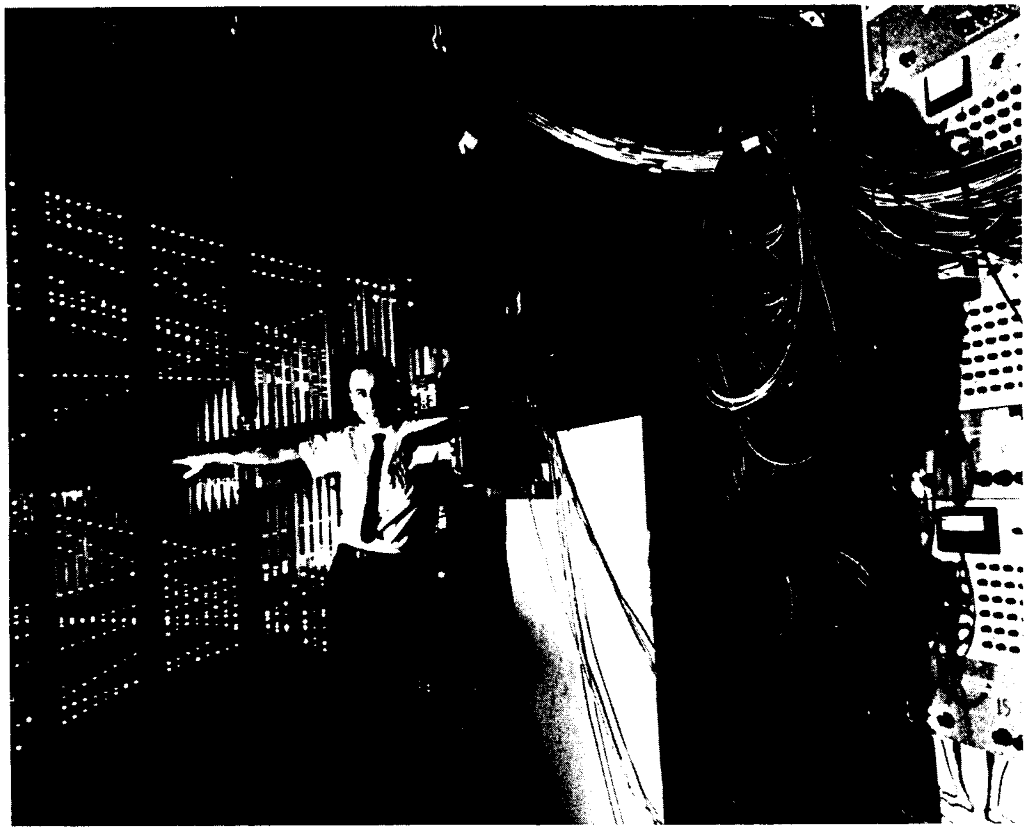
In 1960 Professor Schwartz at Columbia University pointed out that the new generation of accelerators was capable of producing beams of neutrinos (from the decay of beams of high energy mesons) of sufficient intensity to carry out experiments to study the weak interaction at high energy.*

In a companion paper, Columbia Professors Lee and Yang noted that the neutrino (ν) from nuclear β decay (e.g., $C^{12} \rightarrow C^{11} + e^{+} + \nu_1$) and the ν from π decay (e.g., $\pi^{+} \rightarrow \mu^{+} + \nu_2$) could not be assumed to be the same particle. Experimental evidence leading to this conclusion was the fact that gamma (γ) decay of the muon ($\mu \rightarrow e + \gamma$) had never been observed, although if ν_1 and ν_2 were the same particle, theory showed that considerations based on unitarity, one of the most fundamental tenets of physics, would require that $\mu \rightarrow e + \gamma$ should occur in a very small fraction ($\sim 10^{-4}$) of the decays.

Just two years later, when the AGS had come into full operation, a team of experimenters from Columbia and BNL led by Professors Lederman, Schwartz, and Steinberger, carried out an experiment to study ν capture. They established a high intensity, high energy ν beam and observed the ν interactions in a ten ton spark chamber located behind a 13.5-meter iron shield wall which filtered out all particles but ν's. If ν_1 were the same as ν_2, the interactions would have produced μ^{-} and e^{-} in equal abundance. The integrated flux through the spark chamber of $\approx 10^{14}$ neutrinos resulted in only 50 interactions producing energetic events. Of these, 24 showed only a single energetic muon being produced, while the remainder showed muons being produced along with other particles. In no case was a single energetic electron produced. It was therefore concluded that the neutrinos arising from pion decay (ν_μ) are different from those involved in beta decay (ν_e).

This elegant experiment demonstrated the value of the AGS in providing beams of high energy neutrinos as a probe to investigate the nature of weak interactions. It was the forerunner of other work with high energy neutrinos and opened up an entirely new and exciting field of investigation.

* Pontecorvo, in the USSR, had independently come to a similar conclusion.



(Life Magazine photograph)

Professor Schwartz pointing to the ten-ton spark chamber array used to detect the event which led to the discovery of the existence of two types of neutrinos — ν_μ and ν_e.

DISCOVERY OF THE STRONG FOCUSING PRINCIPLE

Since Rutherford, scattering experiments have provided the most fruitful experimental technique to study the fundamental constituents of matter. Cosmic rays have furnished one source of incident particles for scattering experiments. However with the advent of particle accelerators it was obvious that the much more intense and controlled beams of just one type of particle (usually a proton or electron) would lead to much better controlled experimentation and produce results much more quickly. The subsequent rapid development of accelerators resulted in a precipitous increase in the energy of the accelerated particles. However, in the early 1950's it was apparent that a breakthrough in accelerator design was needed.

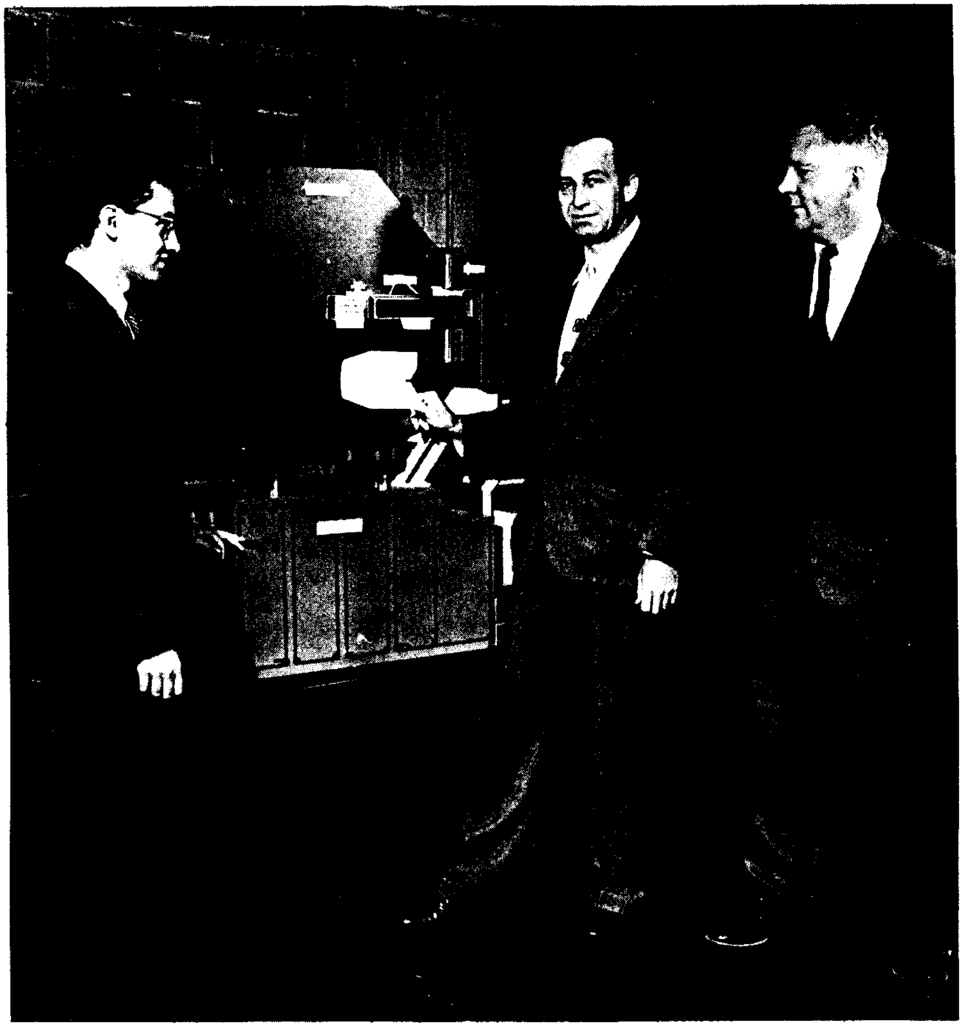
The size of the magnet cross section needed to allow protons to be accelerated to maximum energy in the BNL Cosmotron was determined by the aperture of the magnet gap required to contain the proton beam. The forces focusing the beam within the aperture resulted from shaping the magnet pole pieces to produce a constant radial field gradient. However, the focusing forces were limited to weak values. Increased vertical focusing resulted in decreased radial focusing and vice versa with loss of orbit stability of the beam. To build a weak-focusing proton accelerator like the 3-GeV Cosmotron, but 10 times more powerful would require about 100 times as much steel (~200,000 tons!).

In the Cosmotron C-shaped magnets, saturation of the iron reduced the usable aperture as the field was increased to match the increasing energy of the protons being accelerated. Professor Livingston, on leave from MIT, working at BNL in 1952 on the design of a new higher energy accelerator suggested that reversing every other magnet around the ring would compensate for saturation effects. The BNL theoreticians, Courant and Snyder, studied the particle orbits that would result from such an iron configuration to determine whether they would be stable. They made the surprising discovery that the resulting alternation of the magnet field gradient increased the stability limits so that much stronger focusing forces could be used. Thus the "strong focusing" principle of charged particle optics was discovered and a new era of accelerators came into being. Earlier, Christofilos in Greece had independently made the same discovery, but had not published his results.

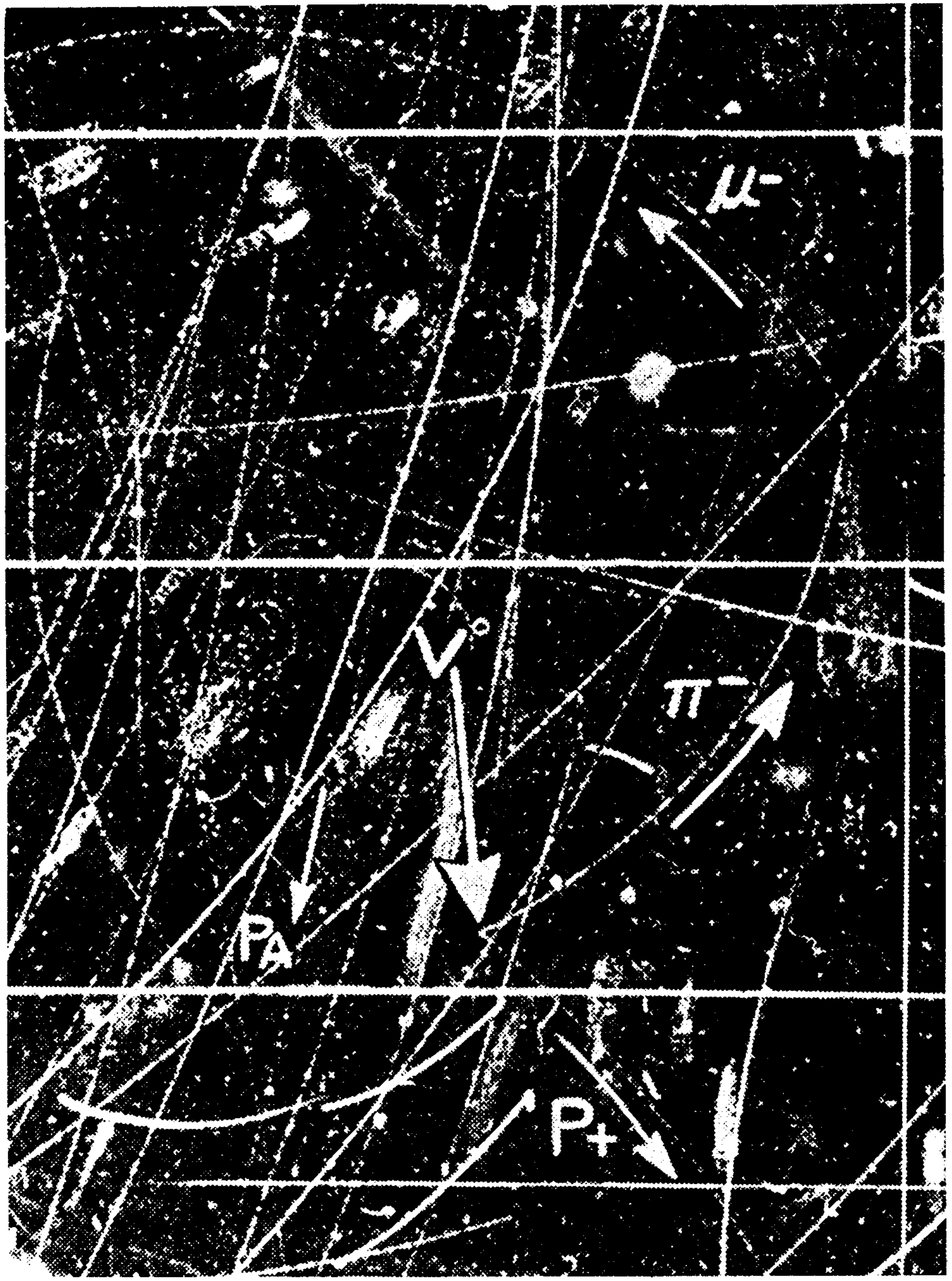
This was essentially a revolution in accelerator design. Much larger accelerators were feasible, since the accelerated beam would be much smaller in size and the magnet cross section could be much smaller. The strong-focusing 25 and 30 GeV alternating gradient synchrotrons were constructed at CERN and BNL using only double the amount of steel (~4,000 tons) needed to construct the weak focusing, 3 GeV Cosmotron.

The recent remarkable advances in particle physics were made possible by these and other accelerators incorporating the strong focusing principle.

The ISABELLE Project, a 400 GeV on 400 GeV colliding beam storage ring accelerator under construction at BNL, would be completely unrealistic without strong focusing.



Courant, Livingston and Synder posed in front of a quarter scale model of the Cosmotron magnet. Professor Livingston is holding a cardboard cutout of a quarter scale strong focusing magnet to illustrate the great reduction in size possible with strong focusing.



DISCOVERY OF THE K_2°

One of the first of the K-mesons discovered in cosmic rays, the θ° meson (now called the K_1° meson) was observed to decay with a mean life of about 10^{-10} seconds, into two π-mesons. It was predicted by Professor Gell-Mann while visiting at Columbia University and Professor Pais of the Institute for Advanced Study that a closely related neutral meson should exist - the θ_2° (now called the K_2°). The K_2° would differ from the original K_1° by having a considerably longer mean life and by decaying into three particles. This would follow if there existed a K° and its antiparticle, the $\bar{K}^\circ$, such that the K_1° and K_2° were composed of different combinations of K° and $\bar{K}^\circ$. The K_1° and K_2° may be thought of as the "true" particles since they have unique lifetimes.

A search for the K_2° was made by Professor Lederman's group from Columbia University working with Chinowsky, a Brookhaven physicist in 1956. They set up a large Columbia cloud chamber for this purpose. Some 8,000 cloud-chamber photographs were obtained using 3-GeV protons from the Cosmotron's external beam. These photographs revealed 23 events with K-mesons which met the predicted requirements: a three-particle decay and (since they traveled 6 meters before decaying) a life-time much longer than 10^{-10} sec.

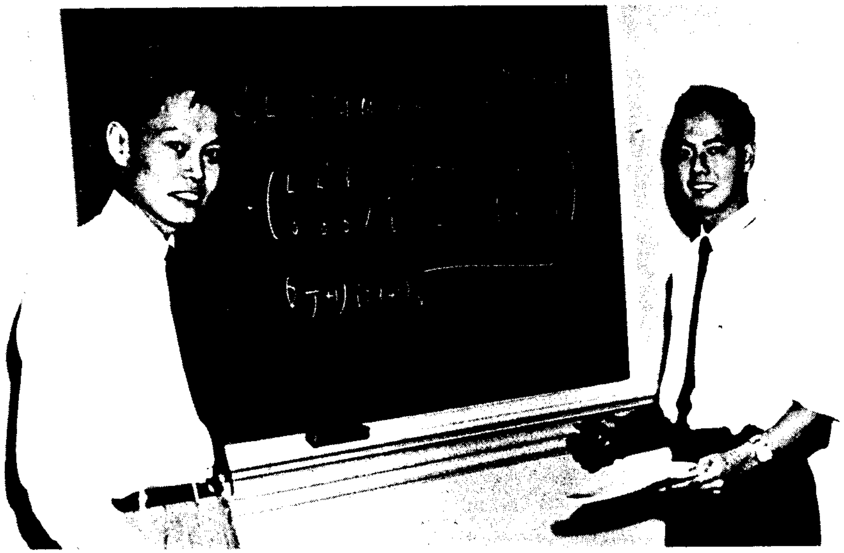
Thus, in a classic example of the complementarity of theory and experiment, it was shown that the K_2° does indeed exist and this confirmed the bold theoretical concept that the K_1° and K_2° were a mixture of the $\bar{K}^\circ$ and K° and further strongly confirmed the existence of strangeness as a quantum number.

A photograph taken of an event in the Columbia University cloud chamber showing a K_2° meson decaying into three particles, a π^+ meson, a π^- meson and a neutral particle (probably a π°). The K_2° has no charge and thus leaves no track in the chamber, but the two charged decay products the π^+ and π^- (the former is labeled P_+ in the photograph) produce the characteristic V° signature (seen at the end of the arrow labeled V°). The neutral decay particle leaves no track, but can be inferred by analysis of the kinematics of the event since the incoming beam momentum and direction are precisely known. The P_+ was shown to be a pion by ionization measurements. The faint track to the right of the shaft of the P_A arrow is a proton track used in the ionization measurement calibration. The π^- decays into a μ^- meson as indicated. Except for the V° the arrows are drawn parallel to the labeled tracks.

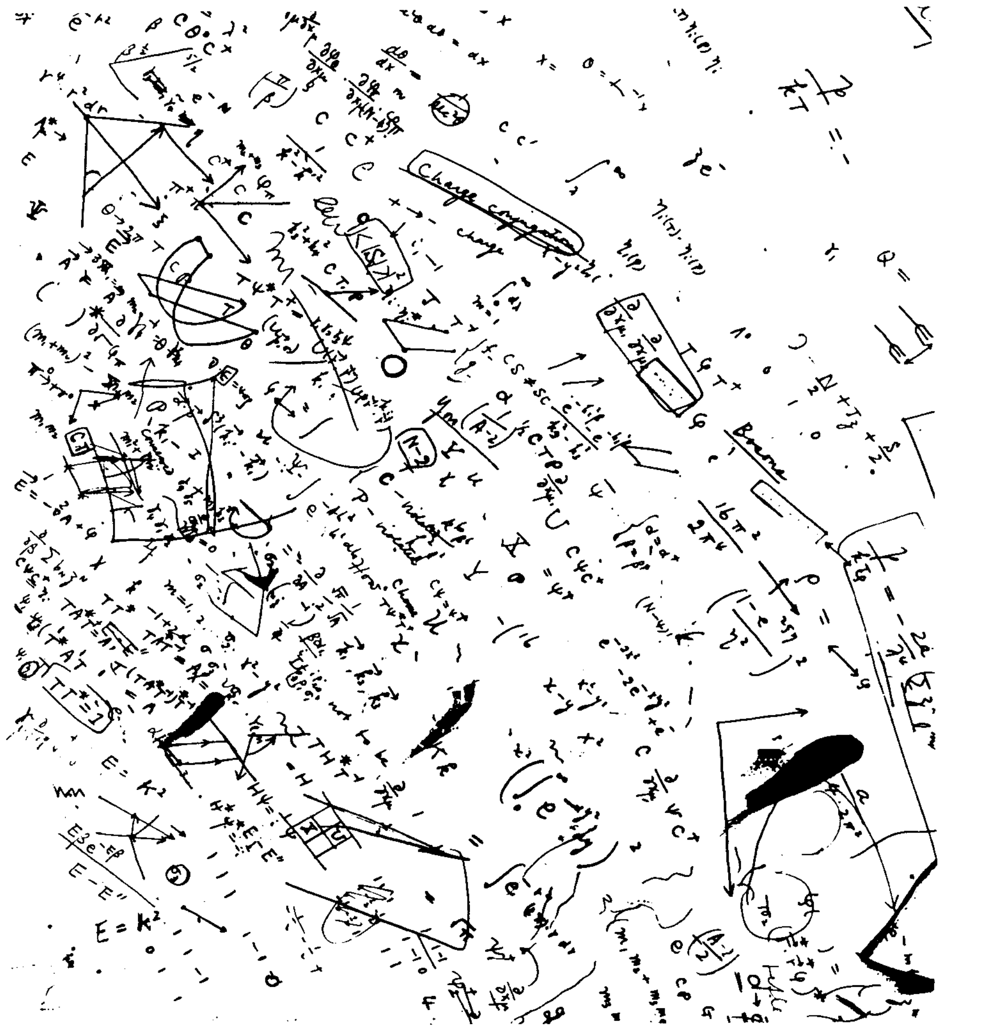
THE τ-θ PUZZLE AND PARITY VIOLATION

The τ-θ puzzle was baffling physicists just at the time that the Cosmotron began producing K mesons. The τ and θ, varieties of the charged kaon, had been discovered in emulsions exposed to cosmic rays and had been found to have the same mass as verified by experiments at the University of California Bevatron. Their long lifetime established that they decay by the weak interaction — the τ into three pions and the θ into two pions. Theory required that if they had different decay modes they must have opposite parity and thus be two different particles in spite of their identical mass values. However, experiments at the Cosmotron showed that their lifetimes and scattering behavior were also identical. It thus became more and more apparent that the τ and θ must be the same particle.

This situation led Professor Lee (Columbia University) and Professor Yang (The Institute for Advanced Study), working at Brookhaven as guest scientists in the 1956 summer program, to question the theory of parity conservation. The rule of the conservation of parity, long considered absolute, means that the mirror image of a reaction is equally probable. After a crucial examination of the experimental evidence they concluded that parity conservation might be violated in weak interactions and suggested experiments to verify their conclusion. This would solve the τ-θ puzzle. They also pointed out that there was no experimental proof that charge conjugation invariance (the physics of a system is unchanged if particles are replaced by their anti-particles) held for weak interactions. The suggested experiments were soon carried out at the National Bureau of Standards and at the Columbia University Nevis Cyclotron Laboratories and beautifully verified their radical conclusions. Lee and Yang were awarded the Nobel Prize in 1957 for this work.



Nobel Laureates Yang and Lee in 1957.



Doodle pad used by Professor Lee during the discussions with Professor Yang while both were visiting scientists at Brookhaven during the summer of 1956. These discussions led to their questioning the conservation of parity in weak interactions and resulted in their being awarded the Nobel Prize. Unlike an experimental attack on a problem the line of thought of a theoretical development can rarely be illustrated. In this case, however, the doodle pad presents to the initiated a rather artistic arrangement of their principal points.

A NEW FIELD OF PARTICLE PHYSICS

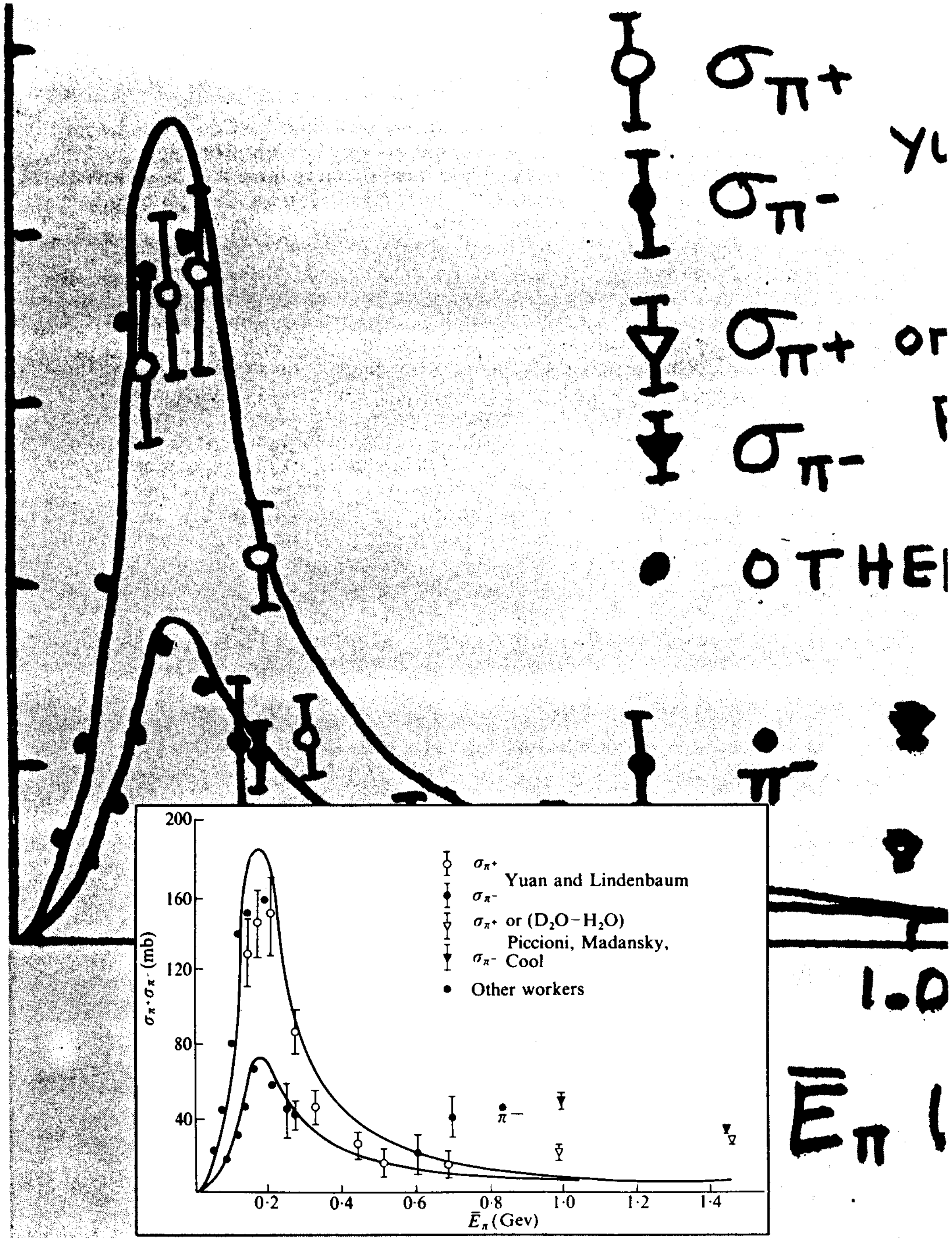
With the discovery of some of the first of a host of new "elementary" particles made possible by the high energy protons available from the Cosmotron, the early Cosmotron experiments contributed greatly to an unexpected new field for high energy physics—resonance spectroscopy.

About a year before the Cosmotron came into operation Professor Fermi and his co-workers using the University of Chicago cyclotron for scattering experiments had discovered a sharp rise in the π^+p and π^-p total cross sections starting at low pion energy (~50 MeV). The π^+ data, still rising rapidly, ended at 136 MeV. Their conclusion regarding the π^- data was that the cross section "seems to level off or perhaps to go through a maximum" at about 175 MeV. The steep rise in both the π^+ and π^- cross sections and the much higher value of the π^+ cross section was a great surprise to physicists. Professor Brueckner at Indiana University attributed the behavior of the cross sections to an I=3/2, J=3/2 "resonance," an excited nucleon isobaric state at about 200 MeV.

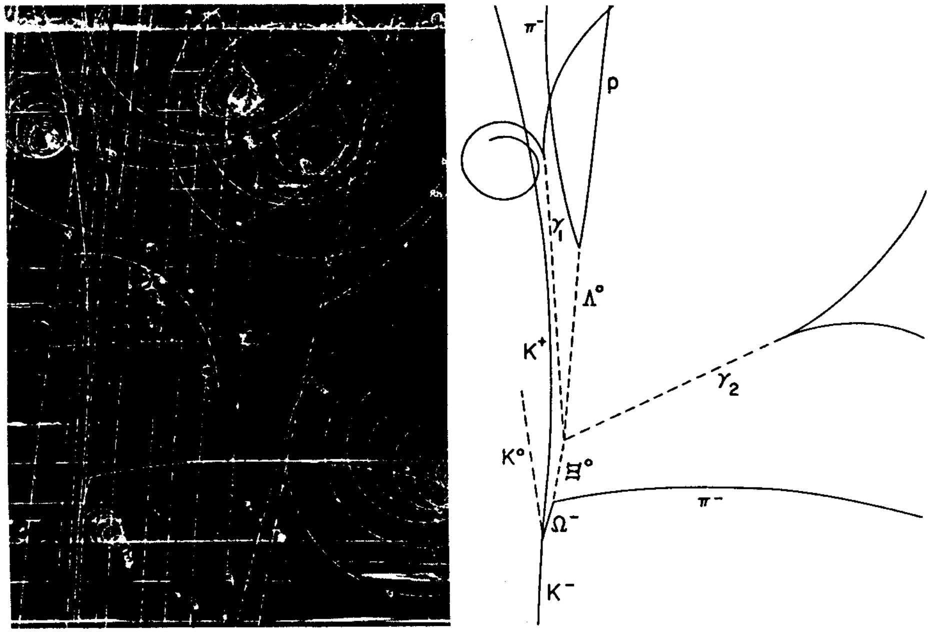
The first additional evidence to support the Brueckner resonance hypothesis of πp scattering came from an experiment at the Cosmotron in 1953 carried out by BNL physicists Lindenbaum and Yuan. The higher energy pion beams which became available early in 1953 enabled them to push the cross section measurements to very much higher energy. Both the π^+p and π^-p total cross sections showed a prominent peak at about 180-200 MeV, characteristic of resonance behavior. The experimenters pointed out that the new data "enhance the possibility of a resonance or near resonance interaction." Other experiments by this group demonstrated that pion production in nucleon-nucleon collisions proceeds predominantly by excitation of one or both nucleons to this I=3/2, J=3/2 resonant state which subsequently decays by emitting a pion.

Subsequent analyses by the BNL Group, the Fermi Group, and others using additional data and analysis techniques firmly established the resonance explanation. The I=J=3/2 resonant state is now known as the Δ particle.

The ensuing proliferation of new "elementary" particles transformed much of "high energy" physics into "particle" physics. Since that time research at Brookhaven has resulted in the discovery of a large share of the new particles.



The early data on $\pi^{\pm}p$ scattering showing the "resonance" peak as sketched by Yuan for the 4th Annual Rochester conference on High Energy Nuclear Physics in December 1954. Data such as this provided the evidence for new "elementary" particles.



The bubble chamber picture of the first Ω^-. An incoming K^- meson interacts with a proton in the liquid hydrogen of the bubble chamber and produces an Ω^-, a K° and a K^+ meson which all decay into other particles. Neutral particles which produce no tracks in the chamber are shown by dashed lines. The presence and properties of the neutral particles are established by analysis of the tracks of their charged decay products and application of the laws of conservation of mass and energy.

DISCOVERY OF THE OMEGA MINUS

As the list of "elementary" particles proliferated, it became obvious to physicists that they must look for some underlying structure composed of still smaller and, hopefully, very many fewer "elementary" particles. Progress in understanding the structure of basic matter, first atomic, then nuclear has, in each case, been preceded by a search for order among the seemingly chaotic multiplicity of entities. This same approach has been followed for the subnuclear world.

In the early Sixties theorists found in group theory a ready-made mathematical description that seemed to provide a remarkably successful scheme for classifying the then known hadrons. This scheme was not based on any underlying theory of fundamental structure, nor was it derived from any abstract principle. It simply provided a concise representation that exhibited symmetry and order and, additionally, predictive power.

The baryons and mesons known at the time fell into symmetric families of multiplets (octuplets, decuplets) sharing two identical quantum numbers (spin and parity), but differing in an ordered way in others (mass, charge, baryon number and strangeness). The mathematical group to fit this complex situation—SU3, the symmetric, unitary group of dimension 3—was proposed independently by Professors Gell-Mann at California Institute of Technology and Ne'eman at Imperial College, London, and named by Gell-Mann "The Eightfold Way." This new classification scheme, it was hoped, might lead in time to an understanding of particle structure just as the classification of the line spectra of atoms, following Balmer's discovery of order in the spectrum of the hydrogen atom, provided the first step leading to quantum mechanics and the understanding of the dynamics of atomic structure.

It was thus very important that the validity of SU3 be demonstrated by experiment. A major prediction was that a particle (named by Gell-Mann the Ω^-), an isotopic singlet with spin = 3/2, positive parity, mass $\approx$1680 MeV, negative charge, baryon number = +1, strangeness = −3, and stable to strong decay, should exist to complete the $3/2^+$ baryon decuplet.

It was therefore a major triumph for the scheme when the Ω^-, a baryon with the precise mass, charge and strangeness predicted, was discovered in 1964 by a team of physicists from BNL, the University of Rochester and Syracuse University, led by Samios of BNL, using the 80" BNL bubble chamber. This crucial experiment also verified the symmetry breaking by medium-strong interactions which accounts for the mass differences within the multiplets.

Since this discovery further developments have led to the concept of "quarks" as the constituents of hadrons and to new higher group symmetry schemes which embody them.

DISCOVERY OF THE J/ψ

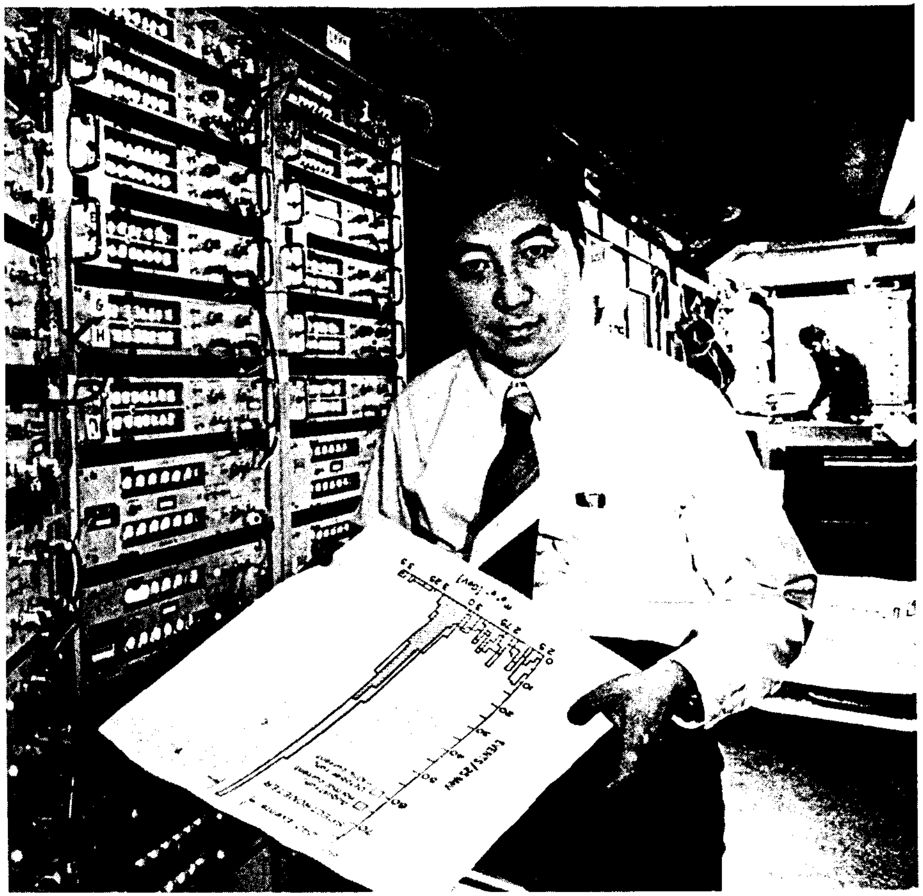
In 1974 an MIT Group, headed by Professor Ting, using a pair spectrometer at the AGS was searching for new resonances from pp interactions in the 1.5 to 5.0 GeV mass region. Motivated by recent indications of resonances in experiments by other groups, including an earlier AGS experiment by a Columbia group studying $p+p \rightarrow \mu^+ + \mu^- + X$ (X=anything), the group in particular were looking at the reaction $p+p \rightarrow e^+ + e^- + X$ for new vector mesons. There was also strong theoretical motivation from the "vector dominance" model (VDM). The VDM explains the electromagnetic interactions of hadrons as taking place through a coupling of the photon (from an electron) with a vector meson (from the hadron) since the photon and the vector mesons have identical quantum numbers (excepting mass). However the VDM had serious deficiencies which could be remedied by the discovery of more vector mesons.

New high intensity proton beams, a result of a recent AGS improvement program, made this experiment possible. Matched with a superb experimental setup, an outgrowth of several previous similar experiments by this group, it combined an elegant experimental technique with an ideal accelerator. Particularly important to the search was the ability of this combination to provide continuous detection of events over a broad range of mass values.

On November 10th the group announced the observation of a sharp peak in the data at approximately 3.1 GeV signaling the discovery of the "J" particle. This was a vector meson resonance (unstable state), about three times the mass of the proton, and incredibly long-lived, a thousand times longer than previously observed massive hadron resonances. Simultaneously a team of experimenters from the Stanford Linear Accelerator Center (SLAC) and the Lawrence Berkeley Laboratory at the University of California at Berkeley headed by Professor Richter of SLAC studying $e^+ + e^-$ annihilations at SPEAR, the SLAC electron storage ring, announced the discovery of the same particle, which they named the "ψ."

The discovery gained immediate acceptance in the high energy physics community, because of the strong validation resulting from observation of the same phenomenon using two completely different experimental methods. Verification by experiments at the Adone electron storage ring at Frascati, Italy and the Doris electron storage ring at DESY, Hamburg, Germany followed within a few days. This history is clear evidence of the value of the multi-laboratory effort in high energy physics.

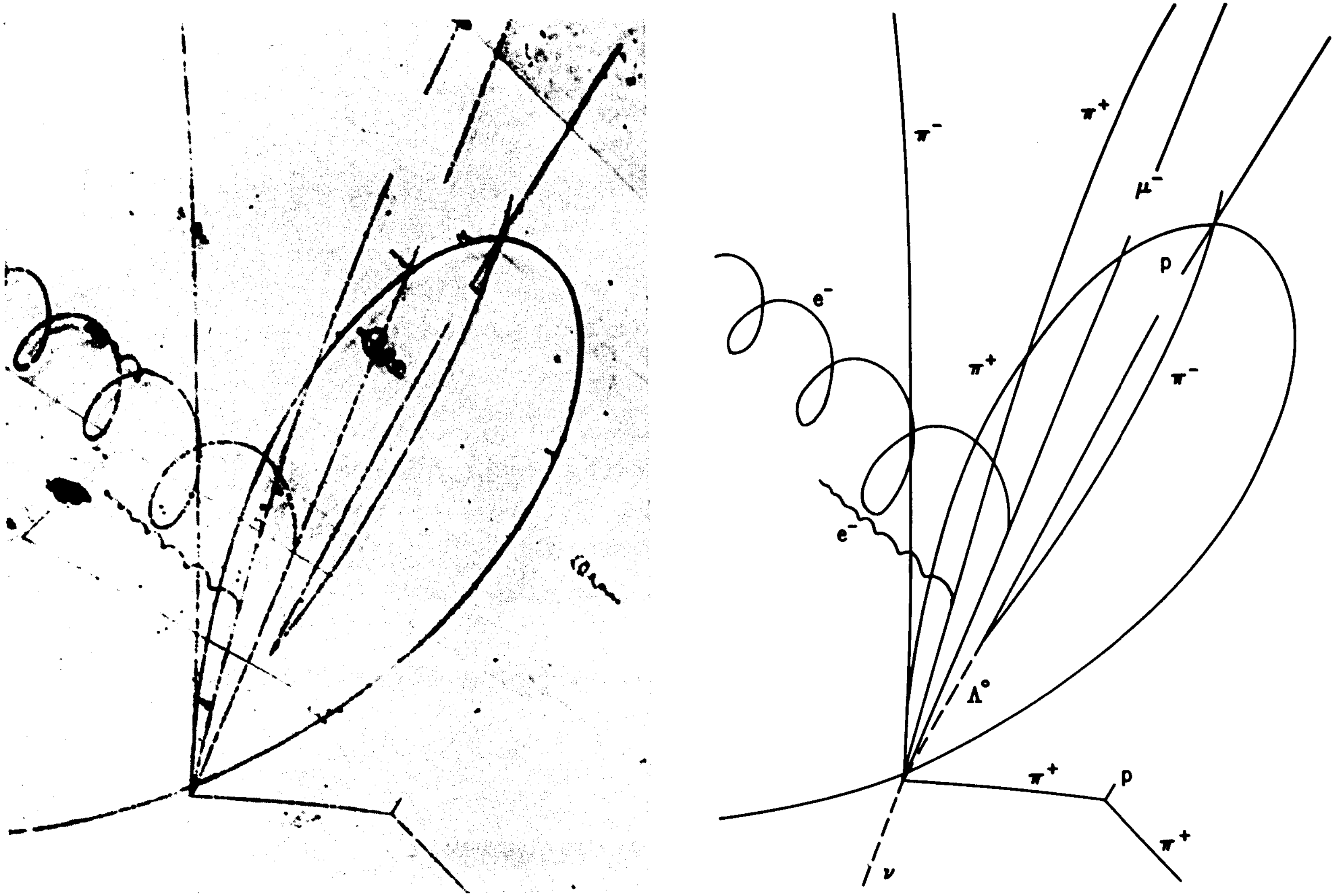
The importance of the discovery was demonstrated by the deluge of theoretical papers attempting to explain the long lifetime of the J/ψ. The high energy physics community was electrified by this completely unexpected new particle which clearly demanded a fundamentally new concept to account for its strange behavior. Many ideas were suggested. Two of the first and most favored suggestions were that the J/ψ was a bound state of a new, heavy quark (the "charmed" quark) or that it was the intermediate vector boson, the exchange particle theorized to mediate the weak interaction. This latter idea was soon shown to be wrong and the former has proven to be the correct explanation. The J/ψ is a bound state of a charmed quark and a charmed antiquark—"charmonium." Its charm was "hidden" since the combination of a quark and an antiquark is cancelling and thus the J/ψ has no net charm which can be observed. This is similar to the "hidden" charge of the atom which is composed of a positively charged nucleus surrounded by negatively charged electrons such that the net charge is zero.



Nobel Laureate Ting in the BNL trailer housing the data acquisition system for the J particle experiment.

The J/ψ was the first of a whole new, unforeseen family of particles (other states of charmonium) which brought with it the need for a fundamental revision in the quark theory of the constituents of hadrons but greatly reinforced the theory. Many other particles have since been found which have "bare" charm (see Charmed Baryon) but the discovery of the charmonium family made it clear that quarks are real dynamical entities, not just a mathematical artifice.

Professor Ting of MIT and Professor Richter of SLAC were jointly awarded the Nobel Prize for what was certainly the greatest discovery in a decade of high energy physics. Further work in ψ spectroscopy is leading to clarification of many of the basic ideas of particle structure.



The photograph of the event in the BNL 7-foot bubble chamber which lead to the discovery of the charmed baryon is shown at the left. The sketch at the right is labeled with the particles involved in the event. Neutral particles, which leave no tracks in the chamber, are shown by dashed lines.

DISCOVERY OF THE CHARMED BARYON

Soon after the three-quark theory was advanced postulating a substructure for the known "elementary" particles, Professors Glashow at Harvard University and Bjorken at the Stanford Linear Accelerator Center (SLAC) proposed a fourth, heavy quark carrying the quantum number charm, mainly on the aesthetic grounds of lepton-hadron parallelism. In 1970 Professors Glashow, Iliopoulos, and Maiani (GIM) had pointed out that there were difficulties in combining the three-quark model with a unified description of the weak and electromagnetic forces, and that these difficulties could be resolved by incorporating in the theory the charmed quark with certain specific properties.

The discovery of neutral currents emphasized one of these difficulties. The existence of neutral currents seemed to require that the neutral kaon should decay into two muons, but experiments at the AGS by groups from Columbia and Princeton, and the University of Massachusetts had shown that this decay mode was so rare that it could not be a result of the neutral current mechanism. GIM showed that a way out of this dilemma was provided by the charmed quark theory which inherently contained a mechanism for the suppression of the neutral current decay of the neutral kaon.

In addition the J/ψ discovery added great impetus to the search for charm which seemed to provide a simple explanation for the existence of this completely unexpected new particle.

The first instance of the production of a charmed baryon was discovered in 1975 by a Brookhaven group led by Samios using the BNL 7-foot cryogenic bubble chamber to study $\nu+p$ interactions. This was also the first example of a particle with "bare" charm as contrasted with the "hidden" charm of the J/ψ.

One way to detect charm is to look for an event which appears to violate the normal rules (just as does the neutral kaon decay mentioned above). The Brookhaven group found an event

$$\nu+p\rightarrow\mu^-+\Lambda^\circ+\pi^++\pi^++\pi^++\pi^-$$

which appeared to violate the $\Delta S=\Delta Q$ rule, well established for low-energy weak interactions. This rule requires that the strangeness change of hadrons in any weak interaction must be matched by the change in hadron charge. In the above interaction the proton with strangeness $=0$ goes into pions (strangeness $=0$) and the Λ° (strangeness $=-1$), so $\Delta S=-1$, whereas the proton with charge $+1$ goes into pions with total charge $+2$ so $\Delta Q=+1$ (lepton charges are ignored) which appears to violate the $\Delta S=\Delta Q$ rule comparing initial and final states. But this is only an apparent effect since by means of charmed quark theory the interaction proceeds by intermediate steps to which the rule does not apply.

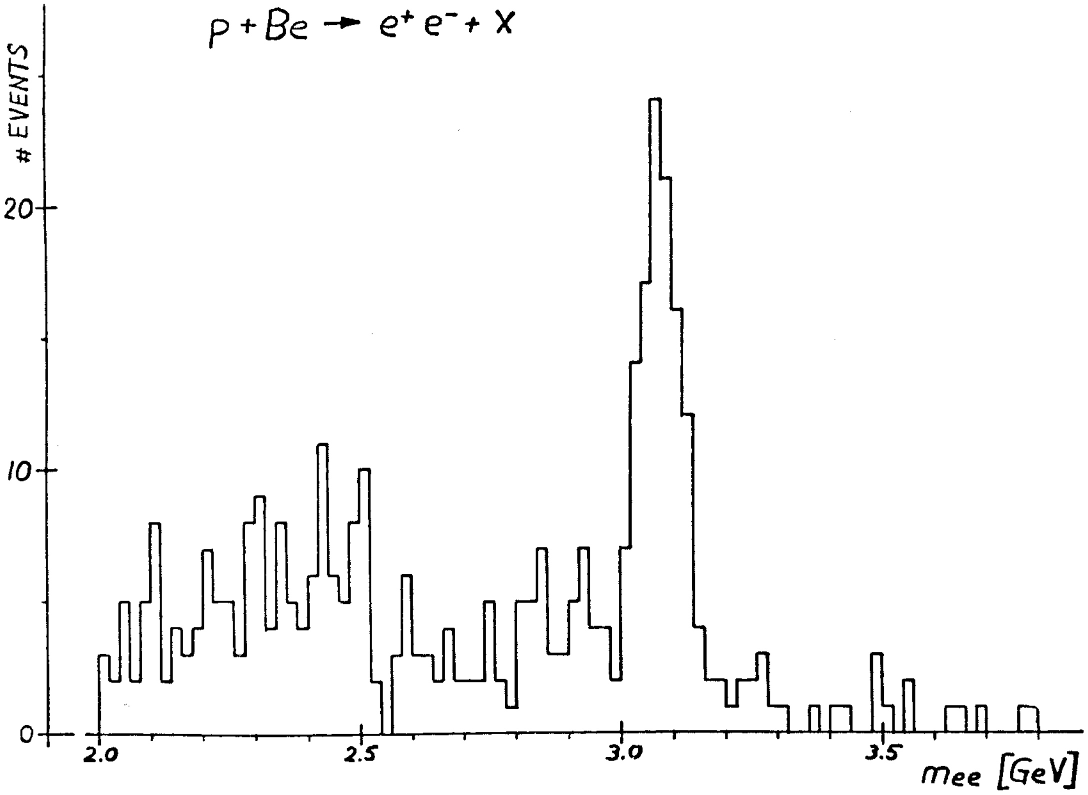
Furthermore Professors De Rujula, Georgi, and Glashow, using gauge theory, had predicted a low-lying charmed-baryon state, the Σ_c^{++}, with charge $=+2$, strangeness $=0$, mass $=2360\ +\!\sim\!100$ MeV, with an expected decay via π^+ emission to another charmed baryon, the Λ_c^+, with charge $=+1$, strangeness $=0$, mass $=2200$ MeV. The Λ_c^+ would then decay via pion emission into the familiar Λ° with charge 0, strangeness $=-1$. Thus the interaction may be rewritten:

$$\nu+p\rightarrow\mu^-+\Sigma_c^{++}$$
$$\quad\llcorner\!\rightarrow\Lambda_c^++\pi^+$$
$$\qquad\llcorner\!\rightarrow\Lambda^\circ+\pi^++\pi^++\pi^++\pi^-.$$

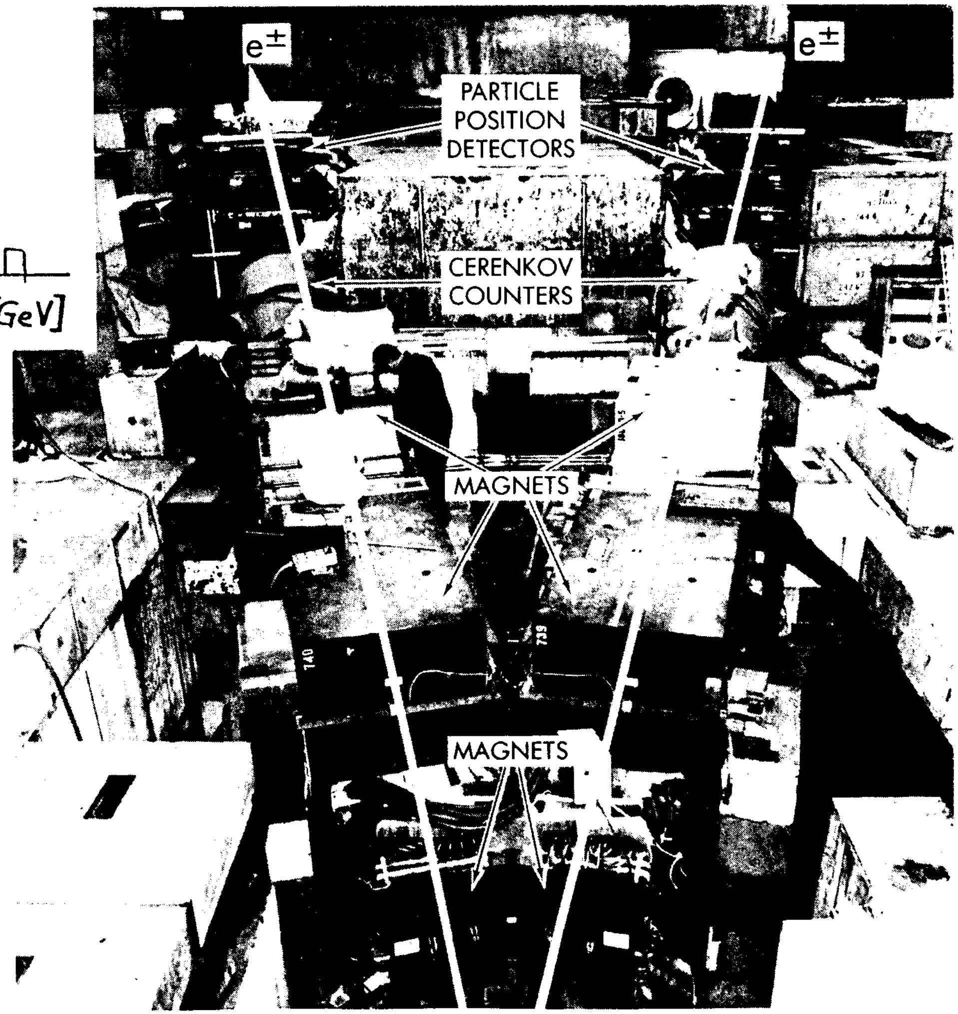
The Brookhaven group observed such an event with a total recoiling hadron mass ($\Lambda^\circ+\pi^++\pi^++\pi^++\pi^-$) of 2426 ± 12 MeV in excellent agreement with the predicted Σ_c^{++} mass $=2360\ +\!\sim\!100$ MeV considering the indicated possible underestimate in the predicted value. The possible decay mass differences ($\Sigma_c^{++}-\Lambda_c^+$) observed are 166 ± 15 MeV, 327 ± 12 MeV and 338 ± 12 MeV depending upon which π^+ meson is taken to be the meson emitted in the decay $\Sigma_c^{++}\rightarrow\Lambda_c^++\pi^+$. The first of these is in remarkable agreement with the Σ_c^{++}(2360 $+\!\sim\!100$ MeV)$-\Lambda_c^+$(2200$+\!\sim\!100$ MeV) predicted decay mass $=160$ MeV.

Additional Σ_c^{++} and Λ_c^+ have since been observed in pictures of events in the 7-foot bubble chamber at the AGS and the 15-foot chamber at Fermilab.

About a year later a group from the Lawrence Berkeley Laboratory working with a SLAC group at SPEAR discovered the D°(1863 MeV), a charmed meson and shortly thereafter additional charmed mesons. Combined with the evidence provided by the charmed baryons and the J/ψ family, these discoveries firmly established the existence of charmed quarks in particular and indeed of quarks in general. This is a necessary element for the Weinberg-Salaam gauge theory which unifies the weak and electromagnetic forces and which would have failed without charm.



The rough graph of the data accompanying the first announcement in the very early morning of November 11th, 1974 of the discovery of the J particle. The sharp peak in the number of events just above 3.0 GeV signalled the existence of this completely unexpected, long-lived, new particle.



The MIT/BNL double armed (pair) spectrometer used at BNL to discover the J-particle. The superimposed sketch shows the paths of the electron and positron through each of the two 70-foot arms of the spectrometer. The three magnets and the Cerenkov counter, in each arm, allow the precise identification of the particles and their energy. The target, into which the 30-GeV protons from the AGS are directed to produce the new J-particle along with myriads of other particles, is out of view at the bottom of the photograph. While operating, the equipment is embedded in nearly 10,000 tons of steel and concrete.

In addition to the discoveries described above that have had immediate and critical impact on the field of particle physics, a number of other important results have added basic information essential to the understanding of this field.

At the time the Cosmotron came into operation cosmic-ray results could not provide a definitive answer to the important theoretical question as to whether more than one meson was produced in a nucleon-nucleon collision (multiple production). Results of n-p experiments by BNL physicists at the Cosmotron directly demonstrated that multiple production occurred.

Using the Cosmotron, a BNL group found the first evidence for the second isobar, the $I=1/2$, $J=5/2$ resonance now designated the N(1688 MeV). A group from the University of Wisconsin discovered the first vector meson, the ρ, which had been predicted theoretically to explain the vector part of the electromagnetic structure of the nucleon. Physicists from BNL, Columbia, and Wisconsin discovered the Σ^0 baryon and another BNL group discovered the Σ^- baryon. The first measurement of the magnetic moment of a hyperon, the Λ^0, was carried out by BNL and University of Rochester physicists, later followed by a very precise measurement made by the BNL group in collaboration with MIT at the AGS. Groups from MIT, Princeton, Pennsylvania and Columbia working at the Cosmotron established the parameters of the $K_{\mu 3}$ and K_{e3} decays.

Using the AGS, the anti Ξ^- hyperon and the antideuteron were discovered by a BNL/Yale group and a Columbia group, respectively. Another vector meson, the ϕ, and the baryon resonance Ξ(1530 MeV) were discovered by a BNL/Syracuse team. The ϕ, the f^0 (discovered at the AGS by a Pennsylvania group), the N(1688 MeV), and the Ξ(1530 MeV) all contributed strong support to the SU3 classification scheme. By means of a total cross section measurement technique of a very high precision, which was developed by a BNL group, about twenty other new resonances were discovered. In fact, a large fraction of all the known resonances have been discovered by experiments done either at the Cosmotron or at the AGS.

Important experiments have been carried out in many other areas of particle physics. Small angle πp elastic scattering by a Brookhaven group showed that the forward dispersion relations (a powerful calculational tool based on microscopic causality) were valid in the realm of distances down to less than 10^{-15} cm. Many measurements of quantum numbers have been carried out with the highest precision ever achieved. These include the magnetic moments of the anti proton and the Σ^-, measured by a team from BNL, California Institute of Technology, Carnegie Mellon, Virginia Polytechnic Institute, William and Mary, and the University of Wyoming. Many important and difficult experiments dealing with the CP violation (discovered at BNL) resulted in precise values of the parameters of the violation. These experiments were performed by groups from Princeton, Columbia, and N.Y.U. The Brookhaven group that carried out the forward dispersion relations check also made the differential cross section measurements which demonstrated that the simple form of the relativistic Regge Pole model did not hold and experimentally established that the Pomeranchuck Theorem (the equality of particle and antiparticle total cross sections at very high energies) could not be valid below 35,000 GeV. This same group did the definitive experiment which established that the controversial split peak of the A_2(1310 MeV) meson (which contradicted quark theory) did not exist. BNL, Columbia, Harvard, Pennsylvania and other groups have made important contributions to the understanding of neutral currents using the unique ν beam at the AGS.

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Robert H. Phillips, December 1981