# OBSERVATIONS in HIGH-ENERGY PHYSICS

*By Leon M. Lederman*

My instructions this morning were to give a survey of the subject we call elementary particle physics, emphasizing the experimental aspects. I will choose what I believe to be interesting and exciting and try to see how we got where we are. The objects we call elementary particles have changed over the years and Fig. 1 is meant to illustrate this.

As you know, the macrobaryon falls just as fast as the macrolepton. The systematic search for the simple objects and their interactions may well have begun with Galileo in Pisa—the first, incidentally, almost vertical linear accelerator.

Figure 2 purports to show that Newton's elementary particles were apples and moons, and in modern language he succeeded, by scattering apples and moons off the earth, in demonstrating the universality of the laws of gravitation. In spite of large apparent differences, moons and apples really behave identically. He must also have been the first to observe the effects of the core in scattering experiments.

In the progression of observation and understanding of the fundamental constituents of matter, the notion of what constitutes elementary particles chronologically involved what we now call chemistry, atomic physics, and then on into the physics of the nucleus. In this dramatic and successful history are contained the great observers and synthesizers—Faraday and Maxwell, Hertz, Michelson and Einstein, J. J. Thomson, Rutherford and Bohr, Compton, Schrödinger, Heisenberg and Dirac, Pauli and Fermi.

In the past ten or fifteen years elementary-particle physics gradually separated from nuclear physics, following the bits and pieces that appeared from higher-energy nuclear disintegrations, and has concerned itself with the structure of the objects which were thought to be more "elementary" and with their interactions.

Thus, the modern phase began in the study of cosmic rays, with the finding of mesons, the construction of the postwar synchrocyclotrons, then the demurely named Cosmotron accelerating protons to 3 BeV at Brookhaven National Laboratory. With the next step to 30 BeV we arrive at "modern times".

Now the most exciting developments have been the uncovering of regularities in the new spectroscopy of elementary particles and the new symmetries of which Professor Gell-Mann has spoken (and, if I may underline this from a plumber's viewpoint, the observed regularities in atomic spectra which in turn gave us the structure of the atom) were related to such symmetries as give rise to the conservation laws of angular momentum and parity. One expects the symmetries underlying elementary-particle spectroscopy (resonances) to be *new* but no less profound.

The rapid progress in the observations of resonances has been made possible by several developments:

Drawings by Nariman Mistry

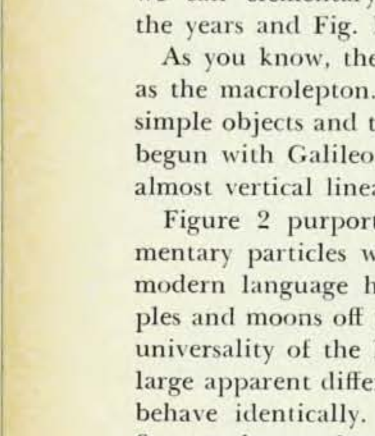

Fig. 1

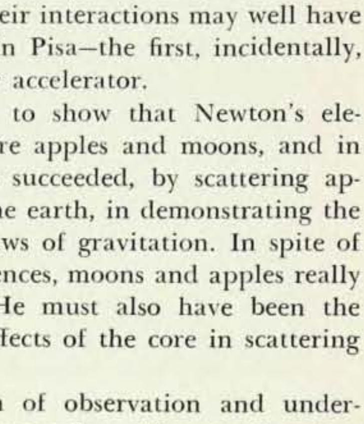

Fig. 2

In 1962, Leon M. Lederman and colleagues discovered there are two kinds of neutrinos—one associated with electrons, the other with muons. Dr. Lederman is director of the Nevis Laboratories and professor of physics at Columbia University.

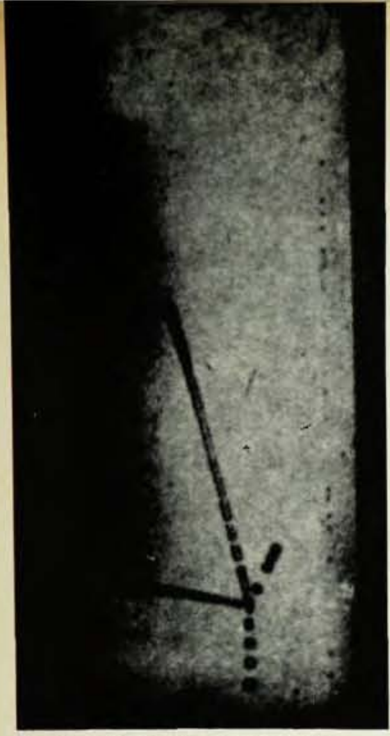

**Fig. 3. 1953 bubble-chamber photo of carbon star in pentane**

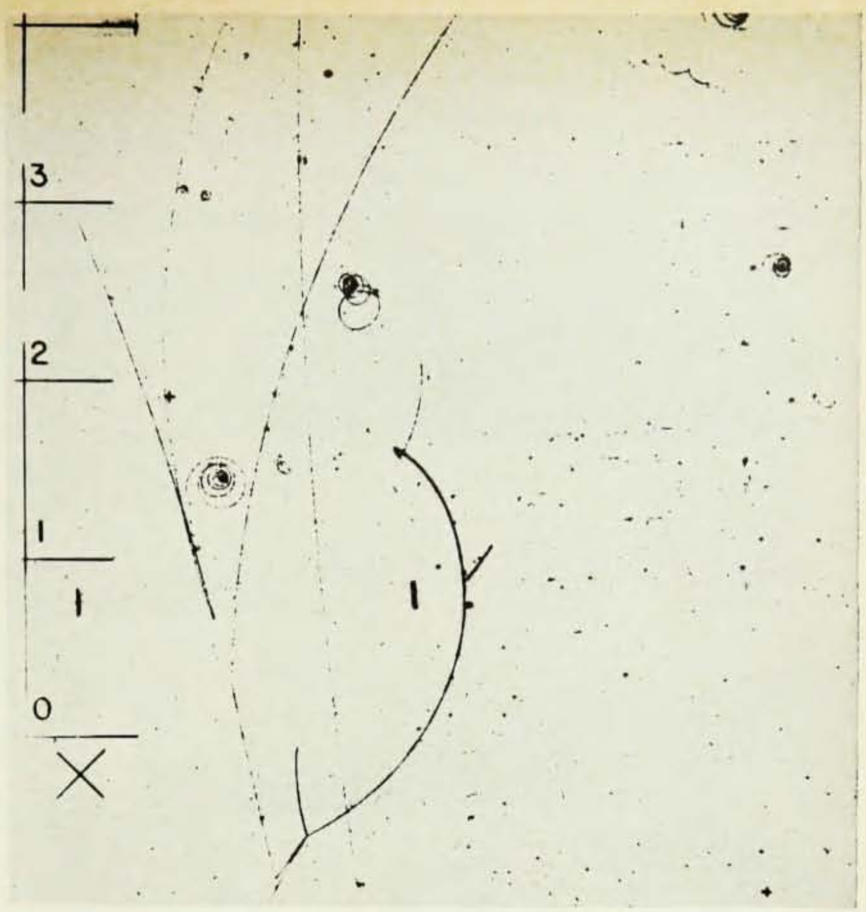


**Fig. 4. 1963 bubble-chamber photograph. Berkeley 72-inch chamber showing reaction $K^- + p \rightarrow K^+ + \Xi^-$; $K^+ \rightarrow \pi^+ + \pi^- + \pi^+$; $\Xi^- \rightarrow \Lambda^0 + \pi^-$; one of the $\pi^+$'s makes a $\pi \rightarrow \mu$-e decay chain. The electron is stable.**

1. The operation of large liquid-hydrogen bubble chambers pioneered by the Alvarez group at LRL after the invention by Glaser and its application to hydrogen by Roger Hildebrand.
2. The application of semiautomatic and automatic data-processing techniques to the resulting film, culminating in the appeal to high-speed computers for ultimate decision as to type of interaction.
3. The operation of the newer AGS (Alternating Gradient Synchrotron) accelerators, and the refinement in particle-beam optics which makes possible clean exposures to particles of well-defined mass and momentum.

Figure 3 is to remind you of the state of bubble-chamber art in 1953. This was about when Glaser succeeded in generating, from the localized effects of ionizing radiation in superheated liquids, a detector predestined to make the forthcoming accelerators fruitful.

Figure 4 is taken from the album of the 72-inch chamber at Berkeley. The power of the technique lies in the liquid-hydrogen medium, the high order of spatial resolution, and the rapid cycling matched to the several seconds' repetition rate of the large accelerators. This photograph illustrates the kinds of reaction which can be observed and studied by the precise angle and momentum measurements made possible by modern data-handling techniques. Incidentally, a new pattern of doing research in high energies is the evolution of instruments so complex and expensive that they are "scheduled" in much the same manner as time on the large accelerators.

The ability to analyze large numbers of photographs has also seen rapid development in the past several years. It is in fact in the midst of a quantum jump in complexity and power—the "old" system is now in current use in many versions among groups working around the Berkeley, CERN, and BNL (Brookhaven National Laboratory) accelerators. It involves scanning on high-quality projection tables (see Fig. 5), three or four

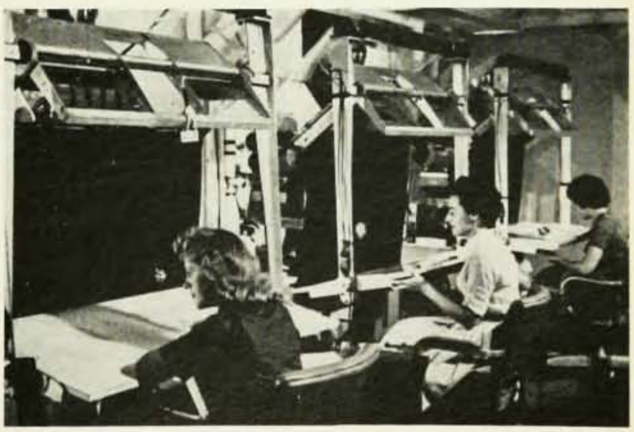

**Fig. 5. Scanning operation**

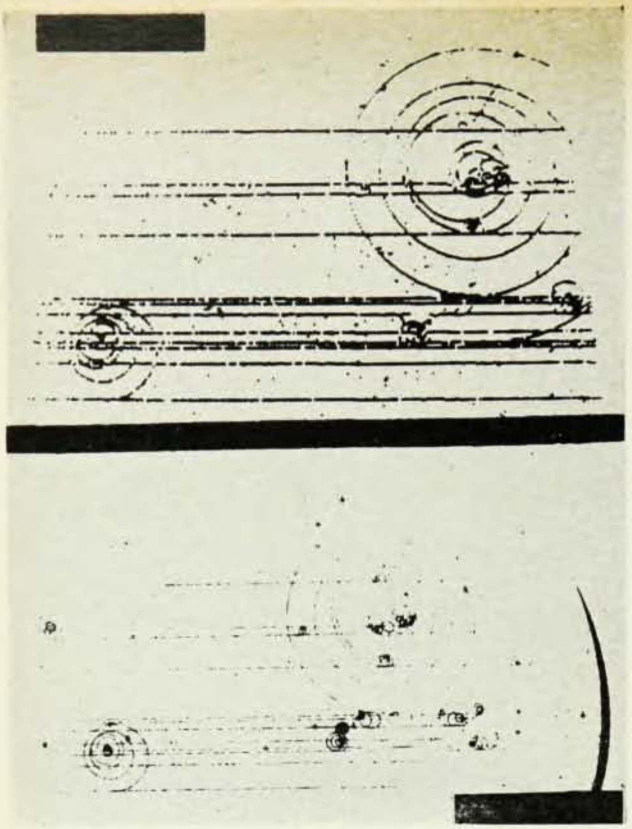

**Fig. 6. Hough-Powell cathode-ray-tube playback (top) and real life picture**

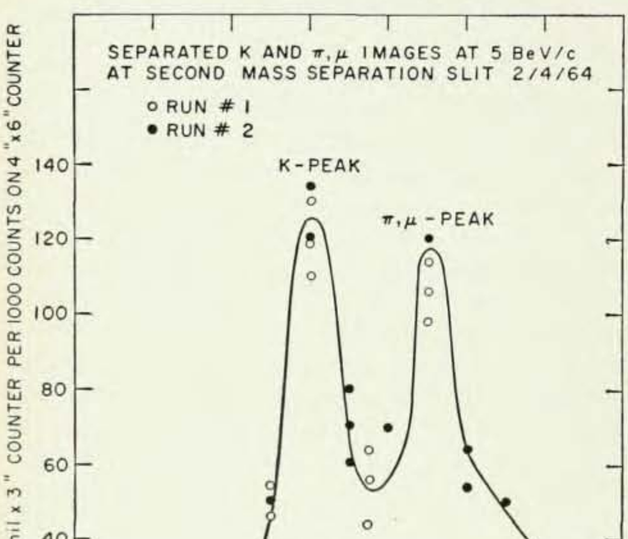


**Fig. 7. BNL separated beam results**

stereoscopic views of the bubble chamber, in order to locate interesting events. In a second step, the events are positioned in measuring machines, and the measuring operator can "punch" the $x$ and $y$ coordinates of various points on the image of the event in each of the several views to a precision of several microns on the film. Various degrees of semiautomation assist the operator in the measuring. The output data, on cards or tape, are then processed in computer programs of great sophistication in order to reproduce the configuration of the event in space through the various optical distortions inherent in the use of real lenses, thick glass windows, liquid-hydrogen medium, etc. The final output presents to the physicist all the physically interesting parameters of the event, with associated errors. Subsequent programs test the configuration against various hypotheses as to the reaction being observed. Finally, other programs assemble the events into histograms and Dalitz plots. This system, operating at Berkeley, examined one million photographs and processed 100 000 events in a year.

The "new wave" of bubble-chamber data handling is illustrated by the so-called Hough-Powell, or Flying Spot Digitizer System: this is designed to dispense eventually with human measurers, to digitize automatically all bubbles on a given film (in the early stages, only those bubbles in previously designated "roads" are recorded). The coordinates of all bubbles intercepted by the flying spot are transmitted to a computer. Figure 6 is a cathode-ray-tube "playback" of a bubble chamber photograph, which had been automatically scanned and stored in a computer memory. More advanced systems are characterized by their names: Automatic Scanning and Measuring System, Digital Automatic Pattern Recognition, Precision Encoding and Pattern Recognizing Oscilloscope.

To obtain clean exposures to monochromatic beams of high purity, very high precision in beam handling has been developed. The accelerator itself is the first example but this will be discussed by Dr. Laslett. The bubble chamber has been the principal customer of the sophisticated "separated" beam transport systems, although we will see other applications later.

A good example is the recently completed 80-inch bubble chamber separated beam designed by Skillicorn and Webster at BNL. It is designed to record separated beams of $K^+$ or $K^-$ up to 6 BeV/$c$ and antiprotons to 8.5 BeV/$c$. Separation is accomplished by classical crossed electrical and magnetic fields in nonclassical strengths and lengths. Beams are transported by strong-focusing quadrupole combinations, with sextupole correcting elements. A measure of the precision is the fact that the physical separation from the rest of the beam of, say, $\bar{p}$ at 8 BeV is of the order of 0.1 inch at a distance of 450 ft from the target! Figure 7 gives some results on the separation. Intensive work is now pro-

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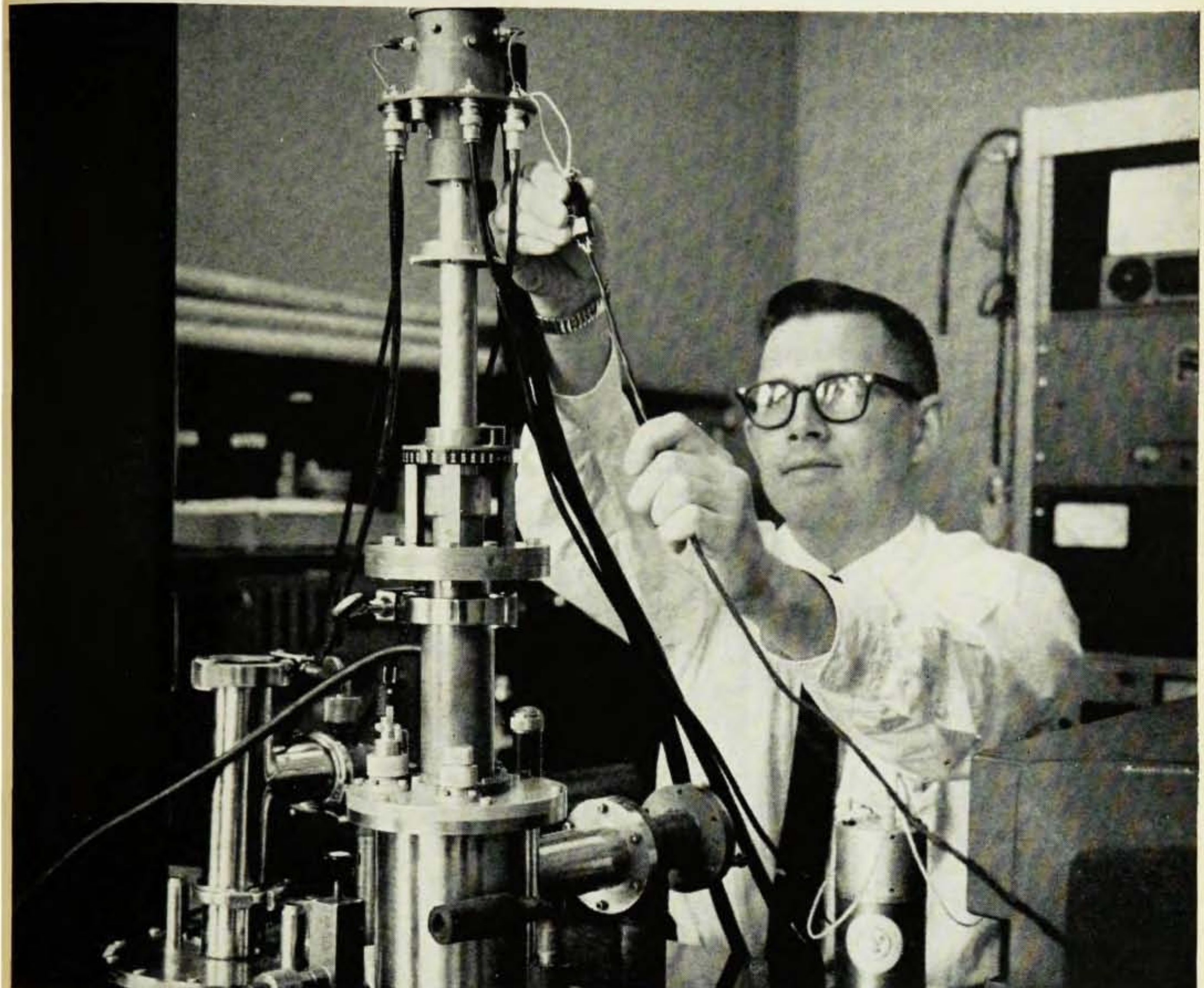

*Dr. C. A. Nanney of Bell Telephone Laboratories, Murray Hill, N. J., uses 50-kg superconducting solenoid for studying electromagnetic wave propagation in various solid-state plasmas.*

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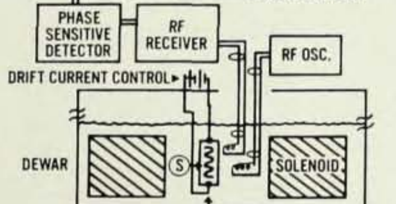


This drawing represents Dr. Nanney's experiment. RF excites helicons which interact with the drift current established by dc current supply. (S) represents solid state plasma wave guide sample.

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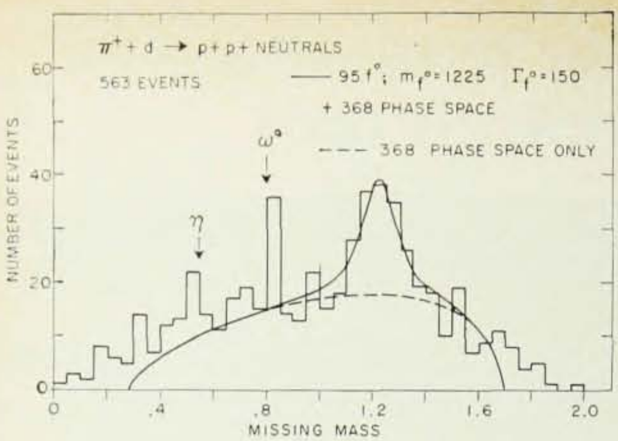


**Fig. 8. Columbia bubble-chamber results on the decay of the f° resonance into neutrals**

ceeding on rf separators which will extend the momentum of separated beams up to that approaching the primary beam.

Now that we have adequate beams, working chambers, and data handling ability, what do we see? We see resonances! How are those isolated? If, like the $\Lambda^0$, or like the $\Omega^-$, they are metastable (prevented by conservation laws or selection rules from decaying via strong interactions) then the weak interactions will bring them down with typical lifetimes of $10^{-8}$ to $10^{-10}$ sec and identification is made by decay modes.

Most of the newly discovered resonances, however, are particles which decay by *strong* interaction in $10^{-23}$ sec. In this case, one observes a production event involving, typically, three or more particles in the final state. If there is a strong interaction—in particular, a quasibound state or resonance—between two or more of these final-state particles at some definite value for the center-of-mass energy, this would reveal itself through an enhancement of the cross section for a certain value of the invariant mass squared, e.g., for a dipion: $M_{ij}^2 = (E_i + E_j)^2 - \mathbf{P}_i + \mathbf{P}_j)^2$.

The assignment of the various quantum numbers $J$ (angular momentum), $I$ (isotopic spin), $G$ ($G$ parity), and $P$ (relative parity), follows from more detailed studies of the production, of other decay modes, and of angular distributions within the mass peak. Figure 8 shows some typical results of the new spectroscopy taken from recent results of the Columbia bubble-chamber group.

Powerful assists to this more fruitful technique have come from counting experiments, e.g., the earliest "elementary" resonance, the 3-3-nucleon isobar, was discovered by quite conventional techniques of scintillation counting. The modern "counterman" calls on nanosecond electronics, gas Cerenkov counters coupled to precision optics, and spark chambers of infinite variety.

A new and exciting possibility is the wide-gap chamber or discharge chamber developed in the USSR, at CERN, and at Harvard by Karl Strauch. Figure 9 shows the remarkable spatial

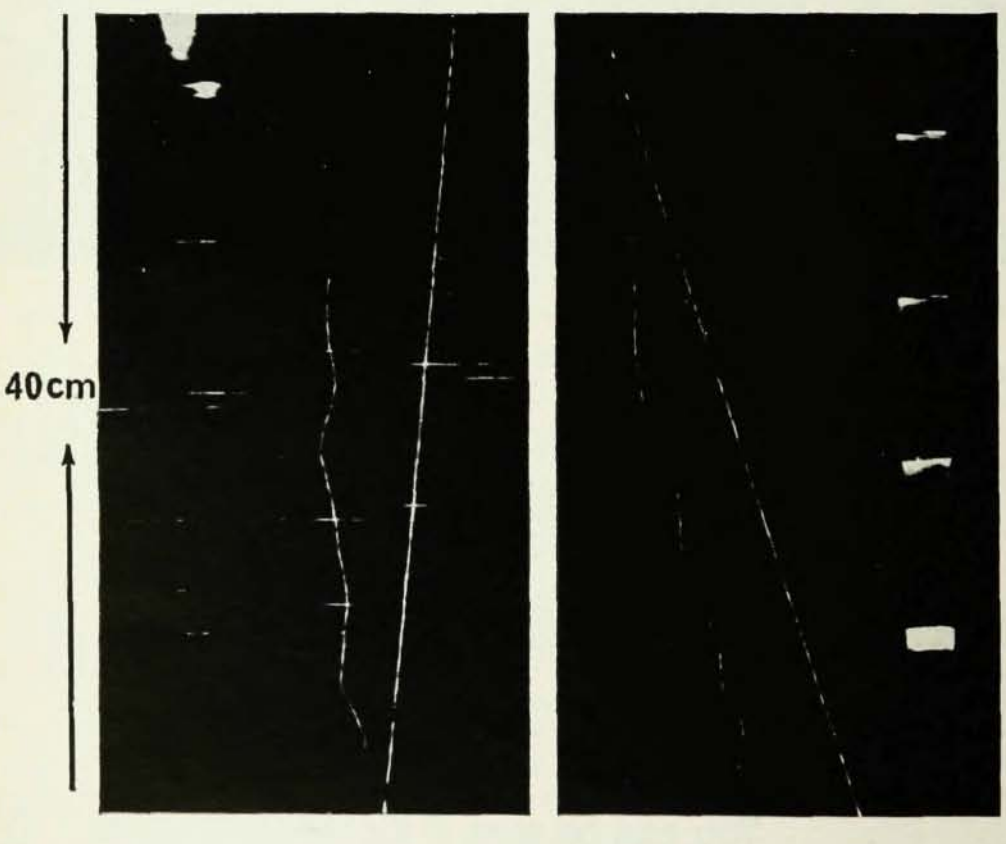


**Fig. 9. Strauch wide-gap discharge spark chamber, showing a fast particle (straight track) and long delta ray; photograph at left is at 0°, at right at 90°**

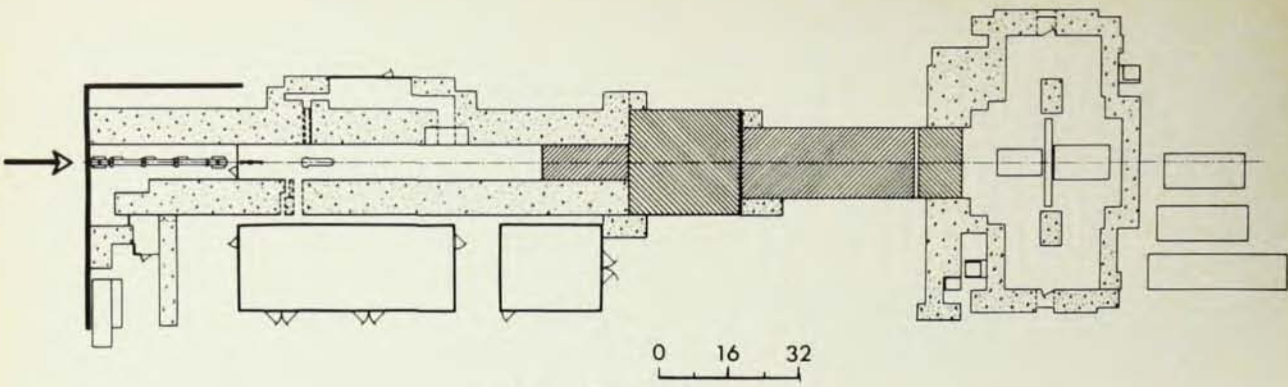


**Fig. 10. BNL neutrino facility**

resolution (for a spark chamber). A combination of the time resolution of spark chambers and the space resolution (and hydrogen) of bubble chambers would be an exceedingly powerful instrument.

I would like to move to a new topic: namely, high-energy neutrino physics. The first experiment establishing the existence of two kinds of neutrinos was in principle exceedingly simple in concept, requiring only an adequate amount of shielding and an extension of the size of spark-chamber detectors (to ten tons). The rate was one event per ten hours. The result established that there exist in nature two neutrinos—one associated with muons and one associated with electrons. It also confirmed the increase in weak interaction cross section with neutrino energy; it served to clarify the grouping of leptons and to account for the heretofore mysterious forbiddenness of many muon reactions. The differences in interaction properties of $\nu_\mu$ and $\nu_e$ have recently been invoked by H.-Y. Chiu to compute the detailed way in which neutrino processes play a role in the supernova explosion of stars. Briefly, at sufficiently high temperature and densities, the muon-type neutrino can more easily dissipate stellar energy, due to its inability to interact with electrons.

Interesting possibilities have been discussed by Morrison, by Cool, Lee, and Schwartz, and by Bahcall and Frautschi, for applying these neutrino-counting techniques to astronomy, for the purpose of observing whether intense radio sources are also sources of high-energy neutrinos and also for the purpose of studying really high-energy interactions.

But to get back—the experiments under way are improved in several ways. The new detectors being used now at CERN and BNL are improved in that the spatial resolution is better and the arrangement is designed to provide more information on the nature of the neutrino-produced particles. The arrangement made possible by extracting the 30-BeV proton beam from the BNL machine is shown in Fig. 10. Some 90 percent of the protons are delivered to a ½-inch-diameter target. Wide-acceptance, highly achromatic focusing devices are employed to decrease the divergence of the pion and kaon beams so that subsequent decay in flight will project neutrinos toward the detectors.

One such device is the so-called "horn of plenty," developed by Van der Meer at CERN. It provides a shaped azimuthal magnetic field with excellent achromatic properties. The combination of external beam, focusing, and larger detectors has resulted in a yield of neutrinos of the order of ten events per hour, an increase of two orders of magnitude since 1961!

The corresponding focusing device in use at Brookhaven National Laboratory, until now less successful but with possibly more promise for future, higher energy neutrino beams, is interesting in that it calls on plasma physics and technology. It consists simply of a uniform, axial high-current discharge. Since the equations of motion of particles in the resulting azimuthal magnetic field are harmonic, one adjusts the tube for a quarter wave

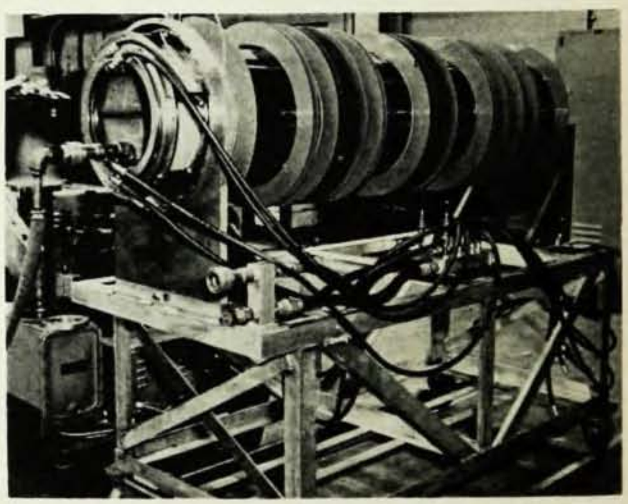

**Fig. 11. Plasma lens at BNL. Longitudinal stabilizing windings shown**

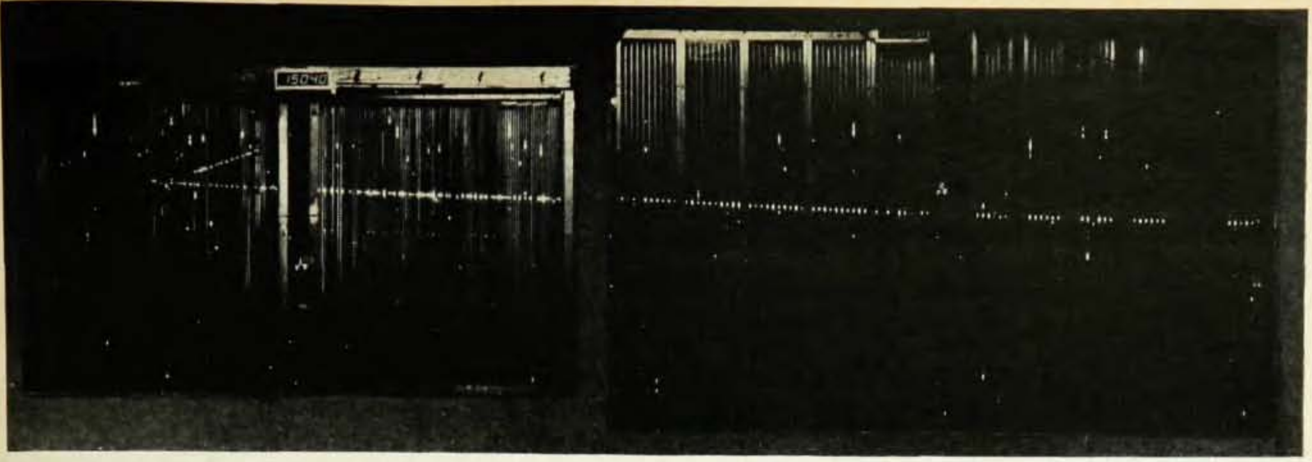

**Fig. 12. Neutrino interaction in Columbia-BNL experiment**

length at the desired momentum—3 to 4-BeV pions. This was tested with the invaluable help of J. Phillips and J. Mather of the Los Alamos Sherwood Project and is now beginning to operate in the external beam at Brookhaven (Fig. 11). A full development of this device as a lens for high-energy particles will certainly involve a better understanding of the dynamics of linear-pinch effect than I believe is now at hand. (First "practical" application of plasma techniques?) That higher energy neutrinos are now being observed is illustrated by the event in Fig. 12. An amount of energy > 4 BeV is observed in this event.

The current neutrino experiments have as their main objectives: (1) to search for the existence of the intermediate boson, W, about which Professor Gell-Mann spoke earlier; (2) to study the nature of the inelastic neutrino collisions; and (3) to study the elastic neutrino events. Preliminary CERN data give some evidence in favor of W existence and fair agreement of the elastic events with theory.

The theoretical prediction of the elastic cross section comes from the rather successful phenomenological *V-A* theory of weak interactions including the conserved vector current theory (CVC).

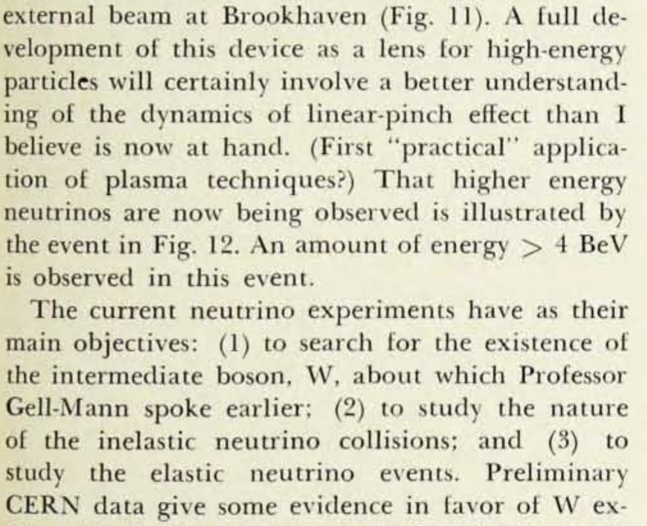


**Fig. 13. Your proton and mine**

Let me recapitulate the history. In 1956 there was a $\tau$-$\theta$ puzzle—the Dalitz plot of final states indicated, to Lee and Yang, the possibility that left-right symmetry (parity conservation) is violated in weak interactions.

The experiments were done on the $\beta$-decay of oriented nuclei, using cryogenic techniques, and shortly afterwards in pion and muon decays. The subsequent brouhaha led, after an exciting and frenetic period of activity in $\beta$-decay and in pion and muon physics, to the *V-A* theory with CVC.

The CVC theory relates the structure of the vector weak interaction current to the electromagnetic form factor of the proton. It thus brings me to the beautiful evolution of our knowledge of the structure of the proton by electron-proton scattering, begun by Hofstadter and continued by the Stanford, Cornell and, now, the Cambridge Electron Accelerator (CEA) group, using its brand new 6-BeV electron synchrotron. The latest experimental situation is shown in the recent electron-proton scattering data by R. Wilson et al. (see Fig. 13).

Recall Rutherford, who sought and found the hard core of the atom—the nucleus. In this search for the internal structure of the proton, the resonances discussed above are one type of observation; electron scattering is another. The charge and current distribution around the proton and neutron are widely thought to be generated by the pion cloud in strong interaction with a nucleon "core."

The data shown here indicate, in fact, no evidence for a core down to radii perhaps $\lesssim 10^{-14}$ cm. It was a kind of triumph that the detailed shape here led to the prediction of objects like the $\rho$ and the $\omega$ pion resonances by Nambu and by Frazer and Falco. These were found but the newer data show that although things are still far from clear,

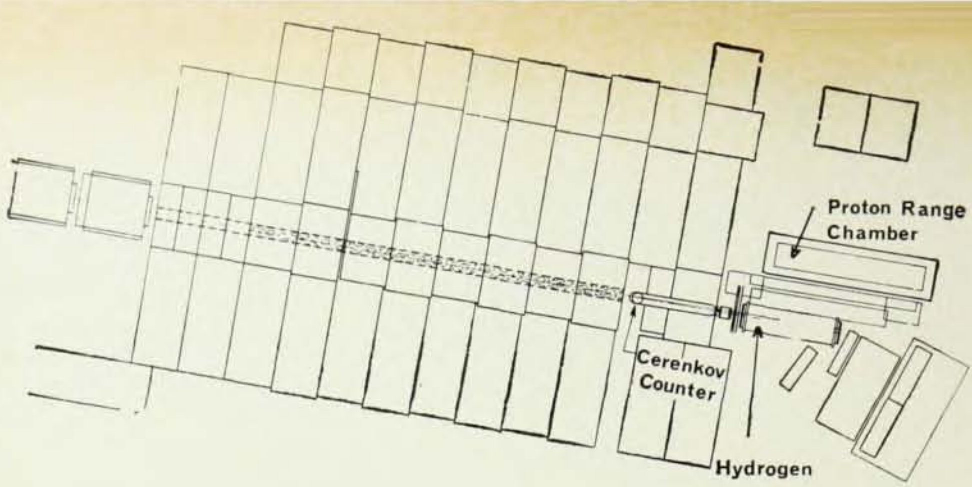


**Fig. 14. Muon-proton scattering arrangement. 14 quadrupole transport (not shown) terminates in 30-foot concrete-filled collimator.**

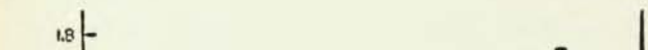


**Fig. 15. Muon-pair production by photons: results**

the role of pion resonances will be essential before this proton photograph is understood.

A parallel situation persists in nucleon-nucleon scattering, a problem which bridges high-energy and nuclear physics. As early as 1938, Breit speculated about a more massive vector meson to account for the short range of the spin-orbit force. Here again it is unlikely that any understanding can be had of the nucleon-nucleon problem without incorporating the pionic resonances.

Scattering experiments not only show the structure of the struck object but also, if any, of the projectile. *In order to search for such structure,* nature seems to have provided us with the muon—in all respects a heavy electron—but is it? A BNL-Rochester-Columbia group is in the midst of a heroic effort to provide the same kind of proton photograph, using the muon light. The AGS is a very good source of muons from pi-mu decay and Fig. 14 indicates the things involved. A 14-quadrupole transport system carries pions and their decay muons a long way from the accelerator, where the pions are filtered by 30 ft of concrete poured into the barrel of a 16-inch battleship cannon. Very large spark chambers detect the scattered muon and recoil proton with energies up to 1 BeV. The proton provides the scale by which the muon and electron can be compared. No results are yet available but any structure to the muon—or the electron—should show in experiments of this kind, down to $\sim 10^{-14}$ cm.

There is reasonably good independent evidence, and the search is continuing, for the validity of Coulomb's law, or better, quantum electrodynamics (QED) down to this very small domain of $10^{-14}$ cm. One is an experiment on muon pair production recently completed at CEA by Kendall, Friedman, et al. (see Fig. 15). Another is the measurement of the anomalous magnetic moment of the muon—at CERN—the so-called *g*-2 experiment. The muon's relatively large mass makes this measurement quite sensitive to behavior at small distances; the agreement with the predictions of QED is excellent to 5 ppm, and provides a test down to distances of $2 \times 10^{-14}$ cm.

The muon *g*-2 experiment is made possible by the parity-violating reaction which generates polarized muons and permits analysis of the muon spin via $\mu \rightarrow e$ decay. This same circumstance permitted a very precise measurement of the hyperfine splitting in the atom muonium, $\mu + e$, carried out at the Columbia cyclotron by the Yale group of Hughes and colleagues (see Fig. 16). With a precision of one part in $10^5$ and a better knowledge of all the remaining physical constants entering, they were able to establish an improved value for the fine structure constant $\alpha$, thus intensifying an intriguing discrepancy between theory and experiment in the *hydrogen hyperfine* structure (meas-

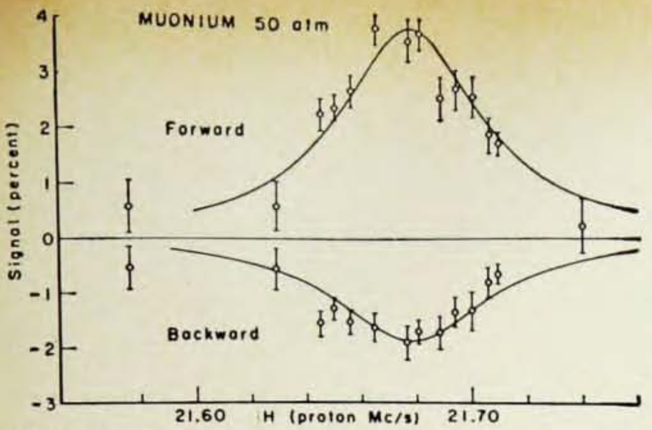


Fig. 16. Muonium resonance curve—Yale at Nevis

ured in a hydrogen maser experiment to 1 part in $10^{11}$) just where the proton form factor, previously shown, makes a significant contribution.

Another way to study the proton structure involves strongly interacting probes and I selected two examples recently carried out at the AGS, one for its idiotic simplicity and one for the technical sophistication which is probably another wave of the future.

The Cornell group (Cocconi-Orear) have done differential p-p scattering up to the highest energy and momentum transfer possible in the AGS. The momentum and angular resolution reduce the background to a very low level, and, combined with the high flux of a primary beam experiment, this yields the amazing curve recently published (see Fig. 17). Incidentally, the solid curve is a fit to the data over the seven orders of magnitude decrease in cross section obtained by Serber from a completely absorbing proton optical model. The data give a complete experimental picture of elastic p-p scattering up to the limits of the present accelerators. It is probably safe to say that there is as yet no theoretical understanding of this picture.

Finally, Yuan and Lindenbaum have arranged to do very precise particle-proton scattering, using all known stable-enough charged particles against protons. The remarkable precision of the results stems from the massive use of scintillation hodoscopes coupled to a computer used "on-line" which feeds results back to the experimenter on the floor. Figure 18 illustrates the logic in "on-line" counting. This is very likely the new wave in electronics experiments analogous to automatic bubble-chamber data analysis. The essential idea is the computation of various interaction parameters, e.g., scattering angle, momentum, etc., in the course of the data taking. It provides the enormous advantage to the experimenter of knowing his results as the run proceeds.

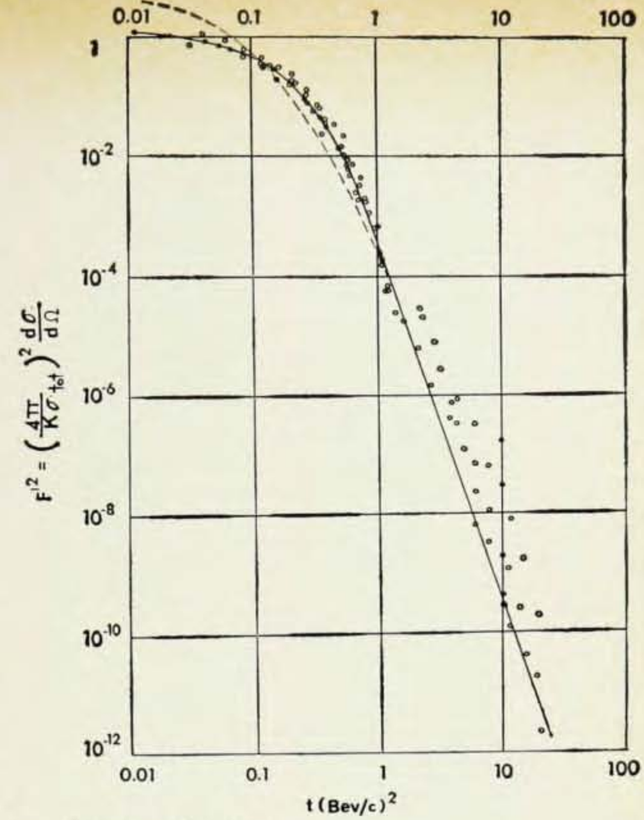


Fig. 17. p-p scattering results

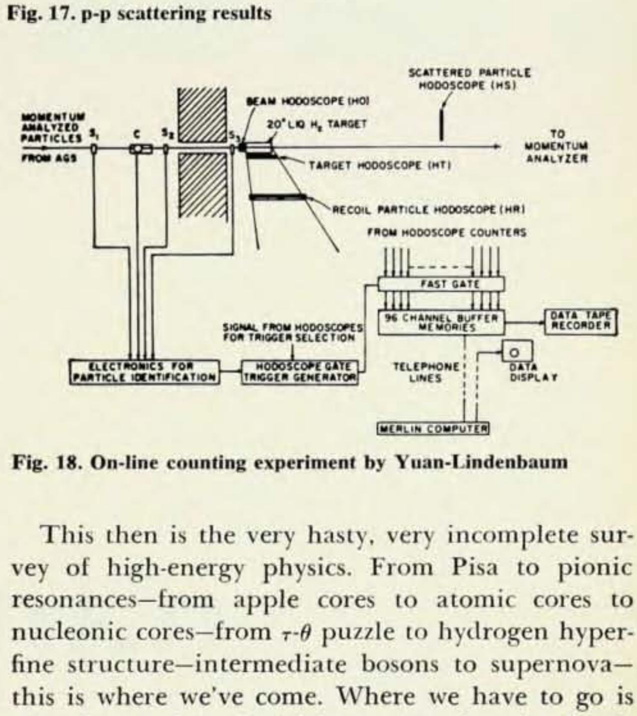


Fig. 18. On-line counting experiment by Yuan-Lindenbaum

This then is the very hasty, very incomplete survey of high-energy physics. From Pisa to pionic resonances—from apple cores to atomic cores to nucleonic cores—from $\tau$-$\theta$ puzzle to hydrogen hyperfine structure—intermediate bosons to supernova—this is where we've come. Where we have to go is also clear and in the higher-energy domain ahead, there is no doubt that the new discoveries will be as fruitful for science and man as they have always been. I think the fears that even God doesn't know what happens at 1000 BeV are groundless. Rather must we marvel at the words of the 19th-Century poet, Francis Thompson:

> All things in heaven and in earth
> Linked are
> That thou canst not stir a flower
> Without troubling a star.