12. In 1980 the households of the elderly had 1.7 persons on average and the households of the nonelderly had about 3 persons. At the same income level individuals in the smaller households could consume more than individuals in the larger households, which implies that for a comparison of economic status household incomes of the elderly should be adjusted upward. The per capita entries are probably too high. Because a child consumes less than an adult, households of the nonelderly have fewer than three adult-equivalent individuals. Therefore, per capita income understates the economic status of the households of the nonelderly.
13. In surveys, the elderly underreport their incomes by much more than other groups (about 37% versus 3%); therefore, the adjustment will increase substantially the incomes of the elderly compared to the nonelderly (*9*).
14. The calculation is based on 5% income growth (*4*, table 5) applied to 1979 taxes and nonmoney income (*9*; table 3), and on 20% and 3% growth in money income of the elderly and nonelderly, respectively.
15. The CPI increased by a factor of 3.11, an annual rate of inflation of 6.7%. This is a high rate by historical standards: during the 17 years before 1967 the CPI increased by a factor of 1.39, an annual rate of just 1.9%.
16. M. Hurd and J. Shoven, in *Horizontal Equity, Uncertainty and Economic Well-Being*, M. David and T. Smeeding, Eds. (Univ. of Chicago Press, Chicago, 1985), pp. 125–172.
17. The poverty level for a single elderly person was $3,479 in 1979, and $4,388 for an elderly two-person household ($5,447 and $6,871 in 1987 dollars). The poverty level is probably far below what most people would think of as poor.
18. T. Smeeding, *J. Policy Anal. Manage.* **5**, 707 (1986).
19. M. Hurd and D. Wise, in *The Economics of Aging*, D. Wise, Ed. (Univ. of Chicago Press, Chicago, 1989), pp. 177–199.
20. R. Burkhauser, K. Holden and D. Feaster, *J. Gerontol.* **443**, S46 (1988).
21. Apparently the elderly do reduce their wealth as they age [M. Hurd, *Am. Econ. Rev.* 77, 298 (1987)].
22. This method of valuing the transfer at market cost is generally used (*7*, *9*). This method (or any other) gives measures that are inherently less accurate than measures of financial wealth because the individuals cannot spend the wealth freely. That is, were the individuals given the Medicare and Medicaid wealth shown in Table 4, they might choose not to spend that amount on the medical insurance policy.
23. Average wealth is taken over those households whose wealth is in the bottom 10% of the wealth distribution.
24. A related point is that Medicare and Medicaid wealth is high because medical needs are high. For example, 68% of Medicaid expenditures in 1984 were for nursing home expenses. As discussed above (*2*), one cannot make utility comparisons across individuals, especially if they have different medical needs; but the availability of Medicaid to finance nursing home expenses, should the need arise, makes an elderly individual better off than were Medicaid not available.
25. Wealth in the SCF is assets less debts. It includes housing, property, businesses, and financial assets. It does not include Social Security, pension wealth, or Medicare and Medicaid wealth.
26. R. Avery and G. Elliehausen, *Fed. Reserve Bull.* 72, 857 (1986).
27. Median household net worth of 45- to 49-year-olds, excluding housing equity, was $11,040 in 1984 (*30*).
28. There is some evidence, however, that saving for retirement has been stimulated by IRAs (individual retirement accounts) [S. Venti and D. Wise, in *Pensions in the U.S. Economy*, Z. Bodie, J. Shoven, D. Wise, Eds. (Univ. of Chicago Press, Chicago, 1988), pp. 9–47].
29. E. Andrews and D. Chollet, in *Social Security and Private Pensions*, S. Wachter, Ed. (Heath, Lexington, MA, 1988), pp. 71–95.
30. Congressional Research Service, *Retirement Income for an Aging Population* (U.S. Government Printing Office, Washington, DC, 1987).
31. R. Burkhauser and J. Warlick, *Rev. Income Wealth*, 27, 401 (1981).
32. M. Hurd and J. Shoven, in *Pensions, Labor, and Individual Choice*, D. Wise, Ed. (Univ. of Chicago Press, Chicago, 1985), pp 193–216.
33. In the RHS, about two thirds of Social Security benefits are windfall gains. The wealthy have larger windfall gains than the non-wealthy (*31*).
34. U.S. Senate Committee on Aging, *Aging America, Trends and Projections.* (U.S. Department of Health and Human Services, Washington, DC, 1988). Because nursing home expenditures are concentrated among the very elderly, their financing will become an important problem as the population ages.
35. The entries under "income" are taken from Smeeding (*9*, table 5). The entries under "adjusted income, household" are from table 4 (*9*). I calculated the other entries under "adjusted income" by multiplying the corresponding entry under "income" by the ratio of "adjusted income, household" to "income, household." Thus, for example, "adjusted income, poverty scale" is (except for rounding error) 0.64 (0.66/0.52). At the individual level, this procedure is accurate for finding adjusted income for the different household scalings.

36. Support from the National Institute on Aging is gratefully acknowledged.

Observations in Particle Physics from Two Neutrinos to the Standard Model

LEON M. LEDERMAN

The two-neutrino experiment established a relationship between particles, muon and muon neutrino, electron and electron neutrino, which evolved into the standard model of particle physics. The theme of this article is a personal one, which reviews a series of experiments at the Columbia Synchrocyclotron, the Brookhaven Cosmotron, the Alternating Gradient Synchrotron, the CERN intersecting storage rings, the Fermilab 400-gigavolt proton synchrotron, and the Cornell electron storage rings, all of which were important in the evolution of the standard model. In some cases the fermion particles were discovered (the second neutrino ν_μ, b quark); in other cases fields of research were opened (muon spin resonance, neutral kaons and charge-parity violation, dimuons and the Drell-Yan process), which led to further development of the standard model. Finally, the current ignorance about the properties of now three neutrinos is reviewed.

IN THIS ARTICLE I WILL DISCUSS A SEQUENCE OF EXPERIMENTS, which eventually, perhaps even tortuously, contributed to the standard model, that elegant but still incomplete summary of all subnuclear knowledge. This model describes the 12 basic fermion particles, six quarks and six leptons, arranged in three generations and subject to the forces of nature carried by 12-gauge bosons. My own experimental work brought me to such accelerators as the Nevis Synchrocyclotron (SC); the Cosmotron and the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL); the Berkeley Bevatron and the Princeton-Penn synchrotron; the SC, proton synchrotron (PS), and intersecting storage ring (ISR) machines at CERN (the European Center for

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Nuclear Research); the Fermilab 400-GeV accelerator; and the electron-positron collider Cornell electron storage rings (CESR). I can only hint at the tremendous creativity that brought these magnificent scientific tools into being.

In particle research not only does one need to have giant machines, one also needs to have some direct experience with the parallel development of instrumentation; with the development of good detectors, my colleagues and I were able to record particular subnuclear events with ever finer spatial detail and even finer definition in time. My own experience began with Wilson cloud chambers; paused at photographic nuclear emulsions; exploited the advances of the diffusion cloud chamber; graduated to small arrays of scintillation counters, then spark chambers, lead-glass high-resolution Cerenkov counters, and scintillation hodoscopes; and eventually involved the increasingly complex arrays of multiwire proportional chambers, calorimeters, ring-imaging counters, and scintillators, all operating into electronic data acquisition systems of exquisite complexity.

Experimentalists are often specialists in reactions initiated by particular particles. I have heard it said that there are some physicists, well along in years, who only observe electron collisions! In reviewing my own bibliography, I can recognize distinct periods, not too different from artists' phases, for example, Picasso's Blue Period. My earliest work was with pions, which exploded into the world of physics (in 1947) at about the time I made my quiet entry. Later I turned to muons, primarily to study their properties and to address questions of their curious similarity to electrons, for example, in order to answer Richard Feynman's question, "Why does the muon weigh?" or I. I. Rabi's parallel query, "Who ordered that?" Muons, in the intense beams from the AGS, turned out to be a powerful probe of subnuclear happenings not only in classical scattering experiments (one muon in, one muon out) but also in a decidedly nonclassical experiment (no muons in, two muons out). A brief sojourn with neutral kaons preceded the neutrino program. This led finally to studies of collisions with protons of the highest energy possible, in which leptons are produced. This last phase began in 1968 and was still going on in the 1980s.

Accelerators and detection instruments are essentials in particle research, but one also needs to have some kind of guiding philosophy. My own approach was formed by a specific experience as a graduate student.

My thesis research at Columbia University involved the construction of a Wilson cloud chamber designed to be used with the new 400-MeV synchrotron under construction at the Nevis Laboratory, located about 20 miles north of the Columbia campus in New York City. Rabi was the Physics Department chairman, maestro, and teacher of us all. He was intensely interested in the new physics that the highest energy accelerator in the world was producing. At one point I described some curious events that I had observed in the cloud chamber, which excited Rabi very much. Realizing that the data were very unconvincing, I tried to explain that we were a long way from a definitive measurement. Rabi's comment, "First comes the observation, then comes the measurement," served to clarify for me the fairly sharp distinction between "observation" and "measurement." Both experimental approaches are necessary for progress in physics. Observations are experiments that open new fields. Measurements are subsequently made to advance these results. Observations may be qualitative and may require an apparatus that sacrifices detail. Measurement is more usually concerned with the full panoply of relevant instruments. And, of course, there are blurred boundaries.

In the course of the next 30 or so years, I was concerned with measurements of great precision, such as the magnetic moment of the muon (*1*) or the mass, charge, and lifetime of the muon (*2*), and with measurements of moderate precision, such as the rho value in muon decay, the elastic scattering of muons (*3*), or the lifetimes of the lambda and kaon particles (*4*). I have also been involved in observations, which are attempts to see entirely new phenomena. These observations have, since 1956, been so labeled in the titles of papers, some of which are listed in chronological order in (*5–11*). I selected these references because they were reasonably important in the evolution of particle physics in the amazing period from the 1950s to the 1980s.

Observation of a Long-Lived Neutral "V" Particle

In 1955, Gell-Mann and Pais (*12*) noted that the neutral K meson presented a unique situation in particle physics. In contrast to π^0, K^0 is not identical to its antiparticle, even though they cannot be distinguished by their decay. Charge conjugation invariance (C invariance) reveals the bizarre particle mixture scheme: K^0 and $\overline{K}^0$ are appropriate descriptions of particle states produced with the well-defined quantum number, strangeness, but two other states, K_L and K_S, have well-defined decay properties and lifetimes.

The essence of the theoretical point, given by Pais in a Columbia University lecture in the spring in 1955, was that there should exist, in equal abundance with the already observed K_S (lifetime, 10^{-10} s), a particle with much longer lifetime, forbidden by C invariance from decaying, as does K_S, into two pions (*12*). The clarity of the lecture stimulated what appeared to me to be an equally clear experimental approach based on the use of the cloud chamber, which had been invented in 1896 by the Scottish physicist C. T. R. Wilson. The cloud chamber was first used in 1911 for making visible the tracks of subatomic particles from nuclear disintegrations. Supplemented with strong magnetic fields or filled with lead plates, it became the workhorse of cosmic-ray and early accelerator research and was used in the discovery of the positron, muon, lambda, "θ" (now K_S), and K^+. As an instrument, it was more biological than physical, subject to poisons, track distortions, and an interminable repetition period of about 1 min. To obtain precise momentum and angle measurements with cloud chambers, one needed luck, old-world craftsmanship, and a large, not-to-be-questioned collection of folklore and recipes. The slow repetition rate of the cloud chambers was a particular handicap in accelerator science. Donald Glaser's invention of the bubble chamber and Luis Alvarez's rapid exploitation of it led to a superior instrument for most purposes, and, by the mid-1950s, very few cloud chambers were still operating at accelerators. At Columbia I had some success with the 11-inch-diameter chamber built at the Nevis SC which I used for my thesis, a comparison of the lifetimes of negative and positive pions (*13*). In a stirring finale to this thesis, I had concluded (wrongly as it turned out) that the equality of lifetimes implied that charge conjugation was invariant in weak interactions.

In its use at Nevis, the cloud chamber produced results on the decay of pions (*14*), on the mass of the neutrino born in pion decay (*15*) (enter the muon neutrino; it would be almost a decade before this number was improved), on the scattering of pions (*16*), including the first suggestions of strong backward scattering that was later found by E. Fermi to be the indicator of the pion-nucleon resonance, and the coulomb-nuclear interference of π^+ and π^- scattering in carbon. The carbon scattering led to analyses of complex optical model parameters, which now, over 30 years later, are still a dominant subject in medium-energy physics convocations.

When the Cosmotron began operating at BNL about 1953, we had built a 36-inch-diameter cloud chamber, equipped with a

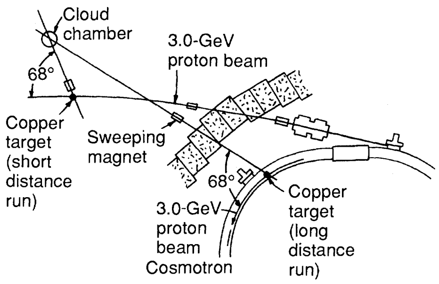

Fig. 1. Experimental arrangements for the study of K_L lifetime. [Adapted from (*18*)]

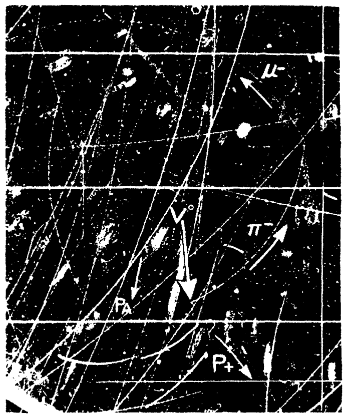

Fig. 2. Example of the reaction: $K^0 \rightarrow \pi^+ + \pi^- +$ neutral particle. P_+ is shown to be a pion by ionization measurements. P_A is a proton track used in the ionization calibration. [Adapted from (*5*)]

magnetic field of 10,000 G, to study the new Λ^0 and θ^0 particles, which were copiously produced by pions of ~1 GeV. This chamber seemed ideal to use in a search for long-lived kaons. Figure 1 shows the two arrangements that were eventually used, and Fig. 2 shows a K_L event in the cloud chamber. The Cosmotron produced ample quantities of 3-GeV protons, and access to targets was particularly convenient because of the magnetic structure of the machine. The trick was to sweep all charged particles away from the chamber and reduce the sensitivity to neutrons by thinning the chamber wall and using helium as the chamber gas. By mid-1956, our group had established the existence of K_L (*5*) and had observed its principal three-body decay modes. Our discussion of alternative interpretations of the "V" events seen in the chamber was exhaustive and definitive. In the next year we measured the lifetime of K_L by changing the flight time from target to chamber (both the cloud chamber and the accelerator were immovable). This lifetime, so crudely measured, is in good agreement with the 1988 handbook value. The K_L was the last discovery made with the now venerable Wilson cloud chamber.

In 1958, we carefully searched the data for the possibility of a two-body decay mode of K_L. This search was a reflection of the rapid pace of events from 1956 to 1958. Whereas C invariance was the key argument used by Pais and Gell-Mann to generate the neutral K mixture scheme, the events of 1957 (see below) proved that, in fact, C invariance was strongly violated in weak decays. Because the predictions turned out to be correct, the improved argument, supplied by Lee *et al.* (*17*), replaced C invariance by charge-parity invariance (CP invariance), and, in fact, also by charge–parity–time reversal invariance (CPT invariance). CP invariance would strictly forbid the decay

$$K_L \rightarrow \pi^+ + \pi^-$$

and, in our 1958 paper based on 186 K_L events, we concluded (*18*, p. 782) that "only two events had zero total transverse momentum within errors . . . and none of these could be a two-body decay of the K_L^0. Upper limits to $K_L^0 \rightarrow \pi^+ + \pi^-$ were set at 0.6% . . . the absence of the two-pion final state is consistent with the predictions of time reversal invariance."

Six years later, at the much more powerful AGS accelerator, Fitch and Cronin and their colleagues (*19*), capitalizing on progress in spark chamber detectors, were able to vastly increase the number of observed K_L decays. They found clear evidence for the two-pion decay mode at the level of 0.22%, establishing the fact that CP invariance is, after all, not an absolute symmetry of nature.

The K^0 research eventually provided a major constraint on the standard model. On the one hand, it served to refine the properties of the strange quark proposed in 1963 by Gell-Mann. On the other hand, the Kobayashi-Maskawa quark-mixing matrix with three generations of quarks was an economical proposal to accommodate the data generated by the K^0 structure and the observation of CP violation. Finally, the neutral K–meson problem (essentially the K_S decay modes) led to the next major observation, that of charge conjugation and parity violation and, together, a major advance in the understanding of the weak interactions. In 1988, neutral K research remains a leading component of the fixed-target measurements at Fermilab, BNL, and CERN.

Failure of Conservation of Parity and Charge Conjugation in Meson Decays

In the summer of 1956 at BNL, Lee and Yang had discussed the puzzle of the K particles (θ, τ puzzle) and were led to propose a number of reactions where possible parity violation could be tested in weak interactions (*20*). At first glance these reactions all seemed quite difficult experimentally, because these were relatively small effects. Only C. S. Wu, our Columbia colleague, attempted, with her collaborators at the National Bureau of Standards, the difficult problem of polarizing a radioactive source. When, at a Christmas party in 1956, Wu reported that early results indicated large parity-violating effects in the decay of ^{60}Co, it became conceivable that the chain of parity-violating reactions, $\pi \rightarrow \mu + \nu$ and then $\mu \rightarrow e + 2\nu$, would not reduce the parity-violating effect to unobservability. The effect here was the asymmetry in the emission of electrons around the incident, stopped, and spinning polarized muon.

Experience in two key areas set in motion a series of events that would convert a Friday Chinese lunch discussion, just after New Year's Day in 1957, into a major experimental observation on the following Tuesday morning. One was that I knew a lot about the way pion and muon beams were formed at the Nevis cyclotron. In 1950, John Tinlot and I had been pondering how to get pions into the cloud chamber. Until that time, external beams of pions were unknown at the existing cyclotrons such as those at Berkeley, Rochester, and Liverpool. We plotted the trajectories of pions produced by 400-MeV protons hitting a target inside the machine, near the outer limit of orbiting protons, and we discovered fringe field focusing. Negative pions would actually emerge from the accelerator into a well-collimated beam. It remained only to invent a target holder and to modify the thick concrete shield so as to "let them out." In about a month, we had achieved the first external pion beam and had seen more pions in the cloud chamber than had ever been seen anywhere (*21*).

The second key area involved my student, Marcel Weinrich, who had been studying the lifetime of negative muons in various materials. To prepare his beam we had reviewed the process of pions converting to muons by decay in flight. What was more subtle, but easy to review during the 30-min Friday evening drive from Columbia to Nevis, was that a correlation of the muon spin relative to its center-of-mass momentum would, in fact, be preserved in the kinematics of pion decay in flight, resulting in a polarized muon beam. One totally unclear issue was whether the muon would retain its polarization as it slowed from ~50 MeV to rest in a solid material. Opportunities to pick up an electron and depolarize it seemed very large, but I recalled Rabi's dictum: "A spin is a slippery thing," and decided, why not try it?

Preempting Weinrich's apparatus and enlisting Richard Garwin, an expert on spin precession experiments (as well as on almost everything else), we began the Friday night activities, which culminated, Tuesday morning, in a 50-standard-deviation parity-violating asymmetry in the distribution of decay electrons relative to muon spin. Figure 3 shows the very simple arrangement. The following ten conclusions were contained in our results (*6*):

1) The large asymmetry seen in the $\mu^+ \rightarrow e^+ + 2\nu$ decay establishes that the μ^+ beam is strongly polarized.

2) The angular distribution of the electrons is given by $1 + a \cos \theta$, where $a = -1/3$ to a precision of 10%.

3) In reactions $\pi^+ \rightarrow \mu^+ + \nu$ and $\mu^+ \rightarrow e^+ + 2\nu$, parity is not conserved.

4) By a theorem of Lee and Yang (*22*), the observed asymmetry proves that invariance under charge conjugation is violated.

5) The g value (gyromagnetic ratio) of the free μ^+ is $+2.00 \pm 0.10$.

6) The measured g value and the angular distribution in muon decay lead to the strong probability that the spin of the μ^+ is 1/2.

7) The energy dependence of the observed asymmetry is not strong.

8) Negative muons stopped in carbon show an asymmetry (also peaked backward) of $a = -1/20$, that is, about 15% of that for μ^+.

9) The magnetic moment of the μ^- bound in carbon is negative and agrees, within limited accuracy, with that of μ^+.

10) Large asymmetries are found for the e^+ from polarized μ^+ stopped in polyethylene and calcium. Nuclear emulsions yield an asymmetry that is half that of carbon.

This large effect established the two-component neutrinos, and this result, together with details of the decay parameters as they emerged over the next year, established the V-A structure (V is the vector interaction, A is the axial vector) of the weak interactions. A major crisis emerged from the application of this theory to high energy, where the weak cross section threatened to violate unitarity. Theoretical attempts to prevent this catastrophe ran into the absence of evidence for the reaction:

$$\mu \rightarrow e + \gamma$$

The rate calculated by Columbia colleague G. Feinberg (*23*) was 10^4 times that of the data. This crisis, as perceived by Feinberg, by T. D. Lee, and by Bruno Pontecorvo, provided motivation for the two-neutrino experiment. The stage was also set for increasingly sharp considerations of the intermediate vector boson hypothesis and, indeed, ultimately the electroweak unification.

The 1957 discovery of parity violation in pion and muon decay proved to be a powerful tool for additional research, and, indeed, it kept the "pion factories" at Columbia, Chicago, Liverpool, CERN, and Dubna going for decades, largely pursuing the physics that polarized muons enabled one to do. The earliest application was the precise magnetic resonance measurement of the muon magnetic moment at Nevis in 1957 (*1*). The high level of precision in such measurements had been unknown to particle physicists, who had to learn about precisely measured magnetic fields and spin flipping. A more profound followup on this early measurement was the multidecade obsession at CERN with the g value of the muon. This measurement provides one of the most exacting tests of quantum electrodynamics and is a very strong constraint on the existence of hypothetical particles, whose coupling to muons would spoil the current excellent agreement between theory and experiment.

One conclusion of the 1957 parity paper stated hopefully (*6*, p. 1417) that "it seems possible that polarized positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei, atoms, and interatomic regions." Today muon spin resonance has become a widespread tool in solid-state and chemical physics, and annual conferences are now devoted to the use of this technique.

High-Energy Neutrino Reactions and the Existence of Two Kinds of Neutrinos

The two-neutrino road (a better metaphor would perhaps be: piece of the jigsaw puzzle) to the standard model passed through a major milestone with the 1963 quark hypothesis. In its early formulation by both Gell-Mann and George Zweig, three quarks, that is, a triplet, were believed adequate along the lines of other attempts at constituent explanations (for example, the Sakaka model) of the family groupings of hadrons.

Before the quark hypothesis, a feeling for baryon-lepton symmetry had motivated many theorists, one even opposing the two-neutrino hypothesis before the experiment because two types of neutrinos suggested that there would be two types of protons. However, after the quark flavor model, Bjorken and Glashow in 1964 (*24*) transformed the baryon-lepton symmetry idea to quark-lepton symmetry and introduced the name "charm." They predicted the existence of a new family of particles carrying the charm quantum number. This development, and its enlargement by the Glashow-Iliopoulos-Maiani mechanism in 1970, was another important ingredient in establishing the standard model (*25*).

In the Glashow-Iliopoulos-Maiani mechanism, the quark family structure and weak interaction universality explain the absence of strangeness changing neutral weak decays. This is done by assuming a charmed quark counterpart to the second neutrino ν_μ. With the 1974 independent discovery of the J/ψ particles at BNL/Stanford Linear Accelerator Center (SLAC) and subsequent experiments establishing the c quark, the standard model, at least with two generations, was experimentally established. Included in this model was the doublet structure of quarks and leptons, for example (u,d), (c,s), (e,ν_e), (μ,ν_μ).

Major neutrino facilities were established at BNL, CERN, Serpukhov, and Fermilab. Out of these laboratories came a rich yield of

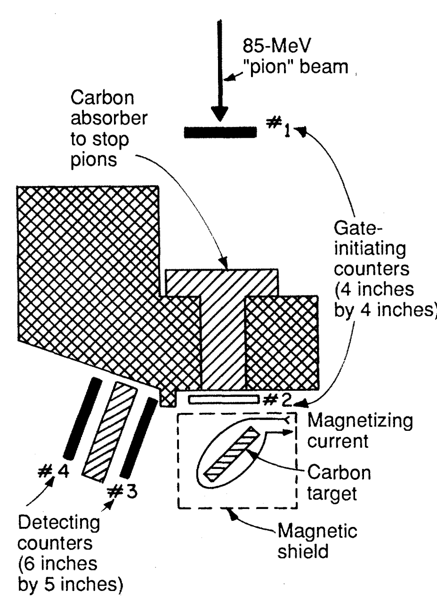

Fig. 3. Experimental arrangement of the parity violation experiment. The magnetizing coil was close wound directly on the carbon to provide a uniform vertical field of 79 G. [Adapted from (*6*)]

information on the properties of the weak interaction including neutral as well as charged currents, on the structure functions of quarks and gluons within protons and neutrons, and on the purely leptonic neutrino-electron scattering.

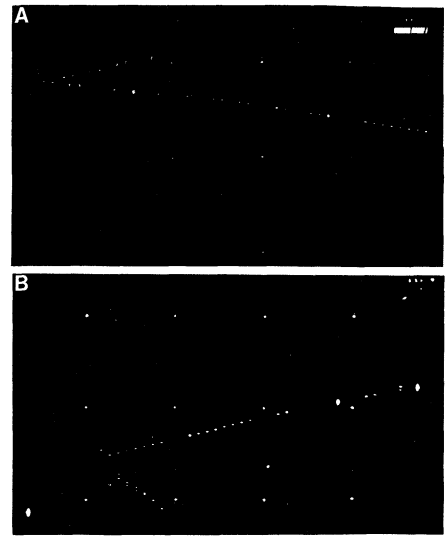

Fig. 4. (A) Neutrino event with long muon track and possible second μ meson. **(B)** Neutrino event with long muon track and possible electron track. [Adapted from (7)]

Partons and Dynamical Quarks

Observation of muon pairs in 30-GeV proton collisions. The two-neutrino experiment moved, in its follow-up phase at BNL, to a much more massive detector and into a far more potent neutrino beam. To provide for this, the AGS proton beam was extracted from the accelerator, not at all an easy thing to do because an extraction efficiency of only 95% would leave an unacceptably large amount of radiation in the machine.

However, the ability to take pions off at 0° to the beam rather than at the 7° of the original experiment, represented a very significant gain in pions and hence in neutrinos. Thus, the second neutrino experiment, now with healthy competition from CERN, could look forward to thousands of events instead of the original 50.

The major motivation was to find the W particle. Invented to carry the weak force, many of the properties of the W particles were known; however, the mass of the W was totally open. The weak interaction theory could predict the cross section for any given mass. The W production is given by

$$\nu_\mu + A \rightarrow W^+ + \mu^- + B$$
$$\bar{\nu}_\mu + A \rightarrow W^- + \mu^+ + B$$

Because W will immediately decay, and often into a charged lepton and neutrino, two opposite-sign leptons appear in the final state at one vertex. Figure 4, A and B, shows W candidates. The relatively low energy of the BNL and CERN neutrino beams produced by 30-GeV protons ($\bar{E} \sim 1$ GeV) made this a relatively insensitive way of searching for W particles, but both groups were able to set mass limits, $M_W > 2$ GeV.

We were then stimulated to try to find W particles produced directly with 30-GeV protons, the signature being a high transverse momentum muon emerging from W decay ($\sim M_W/2$). The experiment found no large momentum muons and yielded (*26*) an improved upper limit for the W mass of about 5 GeV, which, however, was burdened by theoretical uncertainties about how W particles are produced by protons. The technique led, serendipitously, to the development of a new type of high-energy probe.

In the search for W particles, the neutrino-producing target was removed and the beam of protons was transported across the former flight path of 22 m (for pions) and buried in the thick neutrino shield. The massive W could show itself by the appearance of high transverse momentum muons. This "beam dump" approach was recognized in 1964 to be sensitive to short-lived neutrino sources (*27*), for example, heavy leptons produced by 30-GeV protons. However, the single muon produced by a hypothetical W could also have been a member of a pair produced by a virtual photon. This criticism, pointed out by Yamaguchi (*27*), presented us with the idea for a new small-distance probe: virtual photons.

We promptly began designing an experiment to look for the virtual photon decay into muon pairs with the hope that the decreasing yield as a function of effective mass of the observed pair is a measure of small-distance physics and that this slope could be interrupted by as yet undiscovered vector mesons. Observation here would be based on the illumination of virtual photons, whose parameters could be determined from the two-muon final state. In 1967, we organized a relatively simple exploration of the yield of muon pairs from 30-GeV proton collisions. Emilio Zavattini from CERN, Jim Christenson, a graduate of the Fitch-Cronin experiment from Princeton, and Peter Limon, a postdoctoral student from Wisconsin, joined the proposal. Figure 5 shows the apparatus and Fig. 6 shows the data (*8*). Later we were taught (by Richard Feynman) that this was an inclusive experiment:

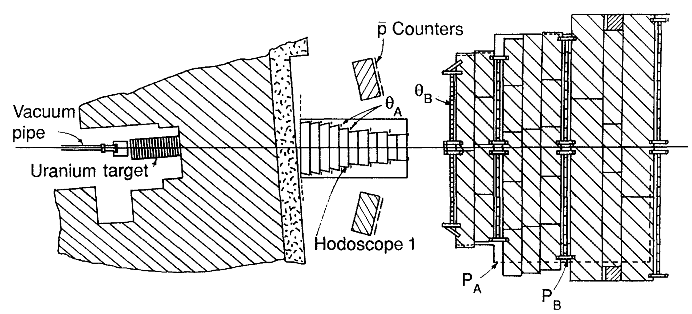

Fig. 5. Brookhaven muon-pair setup; θ_A and θ_B are the production angles of muons A and B; P_A and P_B are the momenta of muons A and B as deduced from the range. [Adapted from (*8*)]

$$p + U \rightarrow \mu^+ + \mu^- + \text{anything}$$

The yield of muon pairs decreased rapidly from 1 GeV to the kinematic limit of nearly 6 GeV with the exception of a curious shoulder near 3 GeV (Fig. 6A). The measurement of muons was by range, as determined by liquid and plastic scintillation counters interspersed with steel shielding. Each angular bin (there were 18) had four range bins, and for two muons this made a total of only 5000 mass bins into which to sort the data. Multiple scattering in the minimum of 10 feet of steel made finer binning useless. Thus we could only note that (*8*, p. 1527) "Indeed, in the mass region near 3.5 GeV, the observed spectrum may be reproduced by a composite of a resonance and a steeper continuum." This 1968–69 experiment was repeated in 1974 by Aubert *et al.* (*28*), who used a magnetic spectrometer based upon multiwire proportional chambers. The shoulder was refined by the superior resolution into a towering peak (see Fig. 6B) called the "J" particle.

Our huge flux of 10^{11} protons per pulse made the experiment very sensitive to small yields, and, in fact, signals were recorded at the level of 10^{-12} of the total cross section. A crucial development from this class of superhigh rate experiments was a foolproof way of subtracting accidentals.

The second outcome of this research was its interpretation by S.

Drell and T.-M. Yan. They postulated the production of virtual photons by the annihilation of a quark and antiquark in the colliding particles (*29*). The application of the now firmly named Drell-Yan process in the unraveling of quark dynamics has become increasingly incisive. It lagged behind the deeply inelastic scattering (DIS) analysis by Bjorken and others in which electrons, muons, and neutrinos were scattered from nucleons with large energy loss. The Drell-Yan process is more dependent on the strong interaction processes in the initial state and is more subject to the difficult problem of higher order corrections. However, the dilepton kinematics gives direct access to the constituent structure of hadrons with the possibility of experimental control of important parameters of the parton distribution function. Indeed, a very large Drell-Yan industry now flourishes at all the proton accelerators. Drell-Yan processes also allow one to study structure functions of pions, kaons, and antiprotons.

A major consequence of this experimental activity, accompanied by a much greater theoretical flood (our first results stimulated more than 100 theoretical papers), was a parameter-free fit of fairly precise (timelike) data (*30*) of "two leptons out" to nucleon structure functions determined by probing the nuclear constituents with incident leptons. Some of the most precise data were collected by the CERN, Dortmund, Heidelberg, Saclay collaboration group of Jack Steinberger. The agreement of such diverse experiments on the behavior of quark-gluon constituents went a long way toward giving quarks the reality of other elementary particles, despite the confinement restriction.

Observation of π mesons with large transverse momentum in high-energy proton-proton collisions. The dynamics of quark-parton constituents were first convincingly demonstrated by Bjorken's analysis and interpretation of the DIS experiments at SLAC in 1970. Feynman's parton approach must also be mentioned. The Berman-Bjorken-Kogut paper (*31*) became the bible of hard collisionists. In 1971, the new ISR at CERN began operations and experimenters were able to observe head-on collisions of 30-GeV protons on 30-GeV protons. The ISR, as the highest energy machine in the 1970s, was a superb place at which to practice observation strategy. Impressed by the power of the dilepton probe at BNL and by its hints of structure, Rodney Cool of Rockefeller University and I convinced Luigi Dilella from CERN to help us design an approach that would trade luminosity for resolution. Recall that with the "beam dump" philosophy at BNL we had been able to observe dimuon yields as low as 10^{-12} of the total cross section. However, the penalty was a resolution roughly analogous to using the bottom of a Coca-Cola bottle as the lens for a Nikon. The balance of resolution and luminosity would be a crucial element in the increasing power of the dilepton process.

We learned from Carlo Rubbia about the excellent properties of lead glass as an electromagnetic spectrometer. Photons or electrons would multiply in the high-Z medium (Z is atomic number) and dissipate all of their energy in a relatively short length. Improved manufacturing techniques had yielded a dense but transparent glass in which Cerenkov light could be efficiently coupled to good quality photomultiplier tubes. The relatively small response of lead glass to pions and kaons as compared to electrons and photons is its great advantage. Six months of hard work with BNL test beams gave us a good command of and respect for this technique and its essential weakness, the calibration process.

The idea then was to have two arrays, on opposite sides of the interaction point, each subtending about 1 steradian of solid angle. The CERN-Columbia-Rockefeller (CCR) team was assembled in 1971 to follow up on the BNL dilepton results, but now electron pairs were the particles of choice and a large lead glass array was in place around the interaction point of this very first hadron collider.

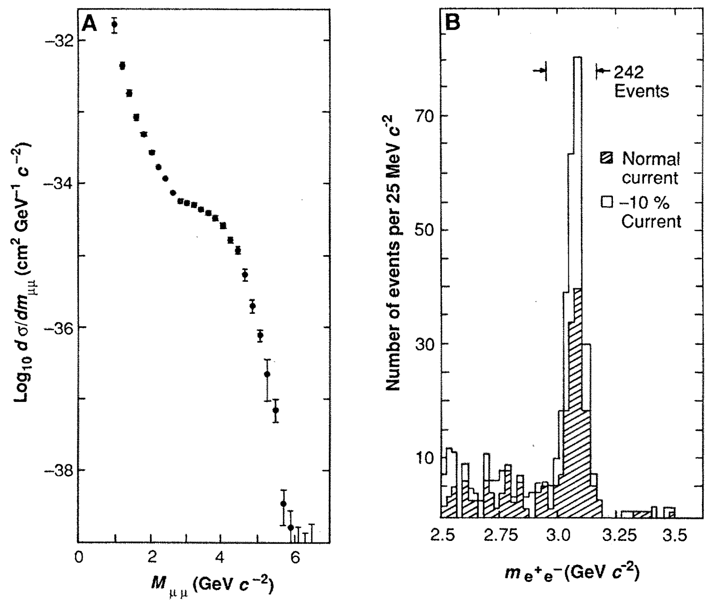

Fig. 6. (**A**) Data on the yield of muon pairs versus mass at 30 GeV; σ, cross section; c, speed of light. (**B**) Dielectron data from the BNL experiment showing the peak at 3.1 GeV that was named "J." [Adapted from (*8*)]

Here again, the discovery of the J/ψ particles was frustrated by an interesting background that was totally unexpected, but a new technique for probing small distances was discovered—the emission of high transverse momentum hadrons.

Before the ISR research, a handy rule was that hadron production would fall exponentially with transverse momentum. The CCR result had, at a transverse momentum P_t of 3 GeV, orders of magnitude higher yield of single π^0 particles, well detected by the high-resolution lead glass array. The production rate was observed to be

$$\sim P_t^{-8} \text{ at } \sqrt{s} = 62 \text{ GeV}$$

($\sqrt{s}$ is the center-of-mass energy), which provided a stringent test of the quark-parton model in the early 1970s and quantum chromodynamics some few years later. Other ISR experiments quickly confirmed the CCR result, but only CCR had the quality and quantity of data to provide a phenomenological fit. It turned out that one could eventually go directly from these data to parton-parton (or quark-quark) hard scattering processes. The study of single inclusive π^0 particles at high P_t evolved into study of the more typical jet structure, which now shows up so spectacularly in proton-antiproton collider data (see Fig. 7).

Thus, the dilepton adventure, based on the use of scintillation counters at BNL and the lead-glass exposures to the ISR, initiated independent programs that contributed to the conviction that protons and pions are bound states of confined quarks that are interacting strongly via the exchange of gluons, which are themselves capable of becoming virtual $q\bar{q}$ pairs.

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

In 1969–70, the BNL dimuon result had stimulated not only the ISR proposal but also a proposal to the Fermilab (then known as the National Accelerator Laboratory) to do a high-resolution lepton pair experiment. By the time the machine came on in 1972–73, a single-arm lepton detector had been installed, which used the very

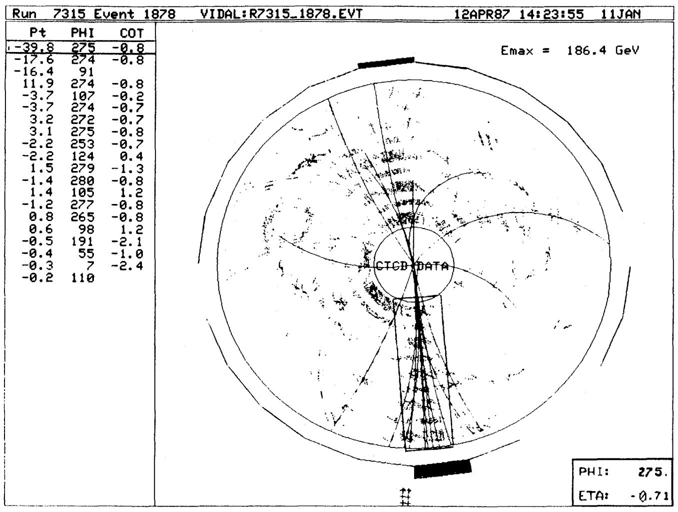

Fig. 7. Collider detector at Fermilab (CDF) dijet at 1.8 TeV; The strong clustering of tracks is called a jet. The back-to-back nature of the two jets is strongly suggestive of an outgoing pair of quarks.

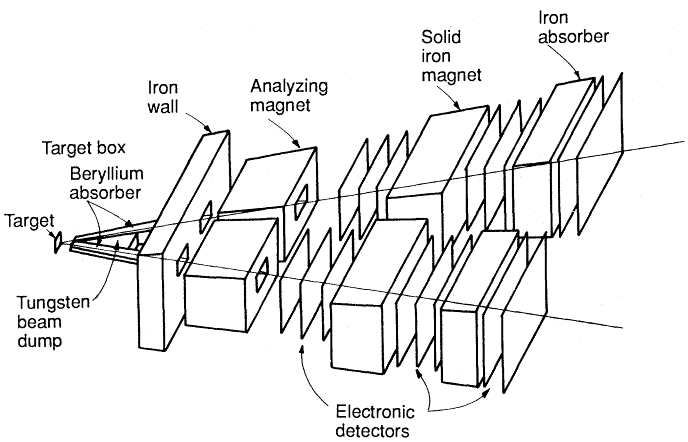

Fig. 8. Schematic sketch of the Fermilab dimuon experiment, which led to the discovery of the upsilon particle. [Adapted from (*10*)]

powerful combination of magnetic measurement and lead glass to identify electrons with a pion contamination of $\lesssim 10^{-5}$. Such a level of rejection is needed when only one particle is involved.

While the study of "direct" electrons fully occupied the Columbia–Fermilab–Stony Brook collaboration in 1974, the J/ψ particle was being discovered at BNL and SLAC. The single lepton effects turned out to be relatively unfruitful, and the originally proposed pair experiment got under way in 1975. In a series of runs, the number of events with pair masses above 4 GeV gradually increased and eventually grew to a few hundred. During this phase, hints of resonant peaks appeared (disrespectfully referred to as "oops-leon") and then disappeared. The group was learning how to do those difficult experiments. In early 1977, the key to a vastly improved dilepton experiment was finally discovered (*10*). The senior Ph.D.'s on the collaboration, Steve Herb, Walter Innes, Charles Brown, and John Yoh, constituted a rare combination of experience, energy, and insight. A new rearrangement of target, shielding, and detector elements concentrated on muon pairs but with hadronic absorption being carried out in beryllium, actually 30 feet of beryllium. The decreased multiple scattering of the surviving muons reduced the mass resolution to 2%, a respectable improvement over the 10 to 15% of the 1968 BNL experiment. The filtering of all hadrons permitted over 1000 times as many protons to hit the target as would have done had open geometry been used. The compromise between luminosity and resolution was optimized by meticulous attention to the removal of cracks and careful arrangement of the shielding. Recall that this kind of observation can call on as many protons as the detector can stand, typically 1% of the available protons. The multiwire proportional chambers and triggering scintillators were crowded in toward the target to get maximum acceptance. Muon-ness was certified before and after bending in iron toroids to redetermine the muon momentum and discourage punch-throughs. Figure 8 shows the apparatus.

In a month of data-taking in the spring of 1977, some 7000 pairs were recorded with masses greater than 4 GeV; a curious, asymmetric, and wide bump appeared to interrupt the Drell-Yan continuum near 9.5 GeV. With 800 events in the bump, a very clean Drell-Yan continuum under it, and practically no background as measured by looking (simultaneously) for same-sign pairs of muons, the resonance was absolutely clear. It was named upsilon and a paper was sent off in August 1977 (*10*). By September, with 30,000 events, the enhancement was resolved into three clearly separated peaks, the third "peak" being a well-defined shoulder (see Fig. 9). These states were called Υ, Υ', and Υ''. Shortly afterward, workers at the DORIS accelerator in the Deutsches Elektron-Synchrotron (DESY) produced the upsilon in e^+e^- collisions and also confirmed the only plausible interpretation of the upsilon as a bound state of a new quark b with its antiparticle $\bar{b}$. The Υ' and Υ'' were then the 2*S* and 3*S* states of this nonrelativistic "atom." In the standard model, we had a choice of charge, + 2/3 (up-like) or − 1/3 (down-like) for the b quark. The Fermilab data favored − 1/3.

"Fallout" was relatively swift. Taken together with the discovery by Martin Perl and his colleagues (*32*) of the τ lepton at SLAC slightly earlier, a third generation was added to the standard model with the b quark at 5 GeV and the τ lepton at 2 GeV. This result fully confirmed the Kobayashi-Mascawa speculation that CP violation may require a third generation. (Clearly, I am vastly oversimplifying the theoretical efforts here.)

The $b\bar{b}$ system was a beautiful addition to $c\bar{c}$ (charmonium) as a measurement laboratory for the study of potential models for the strong quark-quark force. I organized a group from Columbia and Stony Brook to design a lead glass, sodium iodide spectrometer to be used at the CESR machine, ideally suitable for Υ spectroscopy. This Columbia–Stony Brook collaboration began taking data in 1979 and soon assisted in the identification of the 4*S* state (*11*). This state is especially important because it is above threshold for hadronic decay to B states, that is, mesons having one b quark and a lighter antiquark. Followup experiments to learn more about the upsilons were also carried out at Fermilab, in which a number of tricks were used to advance the resolving power even further without losing luminosity (see Fig. 10). By now, many other states, including *p* states, have been identified in this new heavy-quark spectroscopy.

Recent studies of the B states in electron-positron colliders indicate that the B system may be far richer in physics than the charm equivalent, the D system. B^0 particles mix like the K^0 and $\bar{K}^0$ particles. G. Altarelli, one of CERN's leading phenomenologists, has noted that the observation by Argus at DESY of a large amount of B^0-$\bar{B}^0$ mixing constituted the most important experimental result of 1987 in particle physics. There is the strong possibility that CP violation, seen to date only in the K^0 system, may possibly be observable in the B^0 system. B factories, usually high-intensity e^+e^- machines, are being proposed in various laboratories around the world. The Cornell machine is being upgraded to produce of the order of 10^6 $B\bar{B}$ pairs a year. Meanwhile, the hadron machines are being used to solve the very difficult experimental problem of detecting B particles (for example, at the 800-GeV Fermilab fixed target) in a background of 10^6 times as many inelastic collisions. An ambitious detector is being proposed for the Fermilab collider, with the goal of obtaining 10^{10} $B\bar{B}$ pairs per year. On the basis of the 1988 activity, it seems clear that measurements in B physics will play an increasingly important role in particle research over the next decade. The driving force is the recognition that the third generation seems to be needed to account for CP violation. Taken together with baryon nonconservation, CP violation plays a key role in our understanding of the evolution of the universe, including why we are here. For physicists with a less grandiose view, the quark-mixing matrix parameters are part of the basis of our standard model, and b physics is the key to these crucial parameters.

The third generation still needs a top quark, and even as I speak here, searches for this are going on now at the CERN $S\bar{p}pS$ machine and at the Fermilab collider. Both machines are operating at very good intensities, averaging 200 to 400 inverse nanobarns per week. The Fermilab machine has a decided advantage of 1.8 TeV as compared to CERN's 0.63 TeV, but everything depends on the quality of data, the wisdom invested in the design of the detectors, and the mass of the top quark. It does seem safe to predict that a paper will soon appear, perhaps entitled: "Observation of the Top Quark."

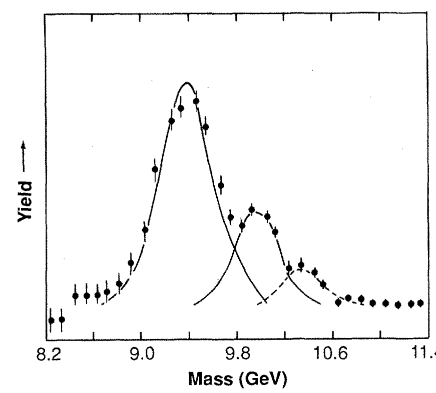

Fig. 9. Peaks on the Drell-Yan continuum with the continuum subtracted. [Adapted from (*10*)]

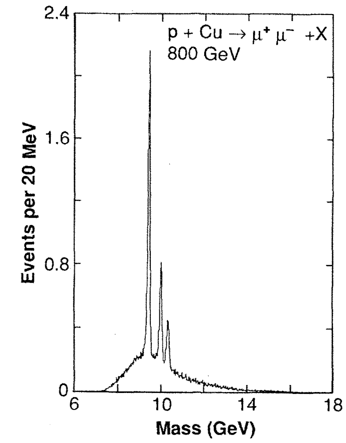

Fig. 10. Fermilab experiment E-605 data. The effective mass of muon pairs is plotted versus yield.

Crucial Issues in Neutrino Physics Today

I conclude this paper with a brief résumé of our ignorance about neutrinos. Neutrino interaction data are in good agreement with electroweak theory of the standard model, and so they will continue to be used to improve our knowledge of quark structure functions and the crucial Weinberg angle. However, we have not yet seen the ν_τ, we do not know if there is a fourth neutrino, we cannot answer urgent questions about the possibility of neutrino mass and the mixing of different flavors, of the stability of the neutrino, whether it has a magnetic moment, and the nature of the antineutrino, that is, whether of the Dirac or Majorana type. Two things make all of this intensely interesting: (i) the astrophysical implications of the answers to these questions and (ii) the likelihood, as expressed by Weinberg, that neutrino mass tells us a lot about some basic questions in particle physics. This is so because, in the standard model, with the usual quarks, leptons, and gauge bosons, there is no possible renormalizable interaction that can violate the conservation of lepton number and give the neutrino a mass. Thus the observation of mass would very likely be a sign of new physics far beyond the standard model, perhaps as far as 10^{15} GeV, the scale of grand unification.

The third neutrino, ν_τ. The "three-neutrino" experiment has not been done. Although data from the decay of τ lepton are very strongly suggestive of the existence of ν_τ, direct evidence for ν_τ has yet to appear.

The technical problem is to move the target as close to the detector as possible but to divert the now unstoppable muons by magnetic sweeping. The flux of ν_τ particles cannot be predicted with confidence, and the shielding configuration is very expensive. This is primarily why the experiment has not yet been done.

A fourth neutrino? This question is a shorthand for the issue of the number of generations. Searches for heavier quarks or leptons are the sine qua non of new accelerators, and these have all been negative so far, although the results simply give limits $M_Q > 40$ GeV (same as the top quark) and $M_L > 20$ to 40 GeV depending on the kind of heavy lepton and on assumptions about the mass of its accompanying neutrino (*33*). Important constraints come from astrophysics where the abundance of helium has been related to the number of low-mass neutrinos (*34*). Probably one more low-mass neutrino could still be accommodated within the Big Bang nucleosynthesis arguments. The connection between the cosmological model of creation in the Big Bang and the number of generations in the standard model is one of the more romantic episodes in the marriage of particle physics and (early universe) cosmology. In fact, one of the strongest supports for Big Bang cosmology is primordial nucleosynthesis: the cooking of the light elements in the caldron beginning at time $t \simeq 1$ s. The astrophysicists manage to get it right: the calculated abundances of deuterium, helium, and lithium agree with what is actually observed in nature. The key is ^{4}He; its abundance is a sensitive indicator of the total radiation density at formation time. Contributing to this are all the low-mass, relativistic particles, that is, photons, electrons, and the three neutrinos, plus their antiparticles. Another generation containing a low-mass neutrino would probably not destroy the agreement, but it would begin to stretch the agreement. There may be a fourth generation, but a fifth generation, which included low-mass particles, would provide a major problem for our astrophysical colleagues. Of course, there could be something out there that is outside of the generational structure. One experiment that is expected to yield results soon is being carried out at the e^+e^- machines at CERN's Large Electron Positron Collider and the Stanford Linear Collider, where the width of the Z^0 will give some indication of the number of neutrino pairs into which it can decay. The residual and dominant current interest in the neutrinos comes from astrophysical arguments related to dark matter. This in turn puts the spotlight on the neutrino mass measurements, to which we now turn.

Neutrino masses and oscillation. In the standard model, neutrino masses are set equal to zero and both total lepton number L and lepton flavor number L_i (i = e,μ,τ) are conserved. Neutrino masses provide a window on the world beyond the standard model and have become one of the outstanding concerns of present-day particle physics. The possibility of oscillation is a statement that $\nu_\mu \rightarrow \nu_e$ is not rigorously forbidden, as suggested by our two-neutrino experiment. The issue is being given great emphasis by cosmologists, who are increasingly turning their attention to the orderly developments of particle physics, and by the solar neutrino crisis, which has been known for decades. This is the discrepancy between the number of ν_e particles observed to be coming from the sun and the flux that our best knowledge would predict. The detection of ν signals from Supernova 1987A has added to the intensity of interest.

The oscillation possibility was first suggested by Pontecorvo in 1967 (*34*). The neutrino flavor mixing is analogous to the quark mixing as given in the Kobayashi-Mascawa matrix. Today we see many attempts to observe oscillations, at the high-energy accelerator laboratories, at meson factories, at reactors, and indeed in the solar environment. That problem is a theoretical one, to understand the lack of neutrinos from the processes that are known to keep the sun shining. The solar neutrino crisis alone is receiving the attention of at least 14 large experimental groups around the world and many times that number of theorists.

As of this date, no convincing evidence for oscillations or for neutrino masses has been observed. These indirect evidences for mass differences and other experiments that look directly for neutrino masses are summarized by:

$$m(\nu_e) <\sim 20 \text{ eV}$$
$$m(\nu_\mu) < 0.25 \text{ MeV}$$
$$m(\nu_\tau) < 35 \text{ MeV}$$

where m is the rest mass. Oscillation limits are more conventionally given in terms of limits on the mass differences, Δ, and the coupled limits on the phase angle, θ, that defines the mixing strength. Slowly and inexorably the space on the two-dimensional plot (Δ^2 versus $\sin 2\theta$) is being reduced to the lower left-hand corner, although logarithmic scales will encourage experimenters to design ever more sensitive tests.

Cosmologists assure us that we live in a universe whose primary component of mass density is dark (nonluminous) and is presently unidentified. Much of this material is probably (they say) nonbaryonic, and some kind of weakly interacting particle carrying some mass (WIMP) is a likely candidate. The principle of minimum complexity would have these be neutrinos, and the condition is $\Sigma m_i \sim 20$ eV ($i = e, \mu, \tau$). This brings the ν_τ forward, as emphasized by Harari (*35*), who proposed as a matter of urgency a renewed search for $\nu_\mu \rightarrow \nu_\tau$.

Other experiments at the new pion factories (Paul Sherrer Institute in Zurich, Tri-University Meson Facility, and Los Alamos Meson Physics Facility) are looking for (small) violations of lepton flavor conservation by extremely sensitive searches for such reactions as

$$\mu^+ \nrightarrow e^+ + \gamma \text{ (again but now at B} \sim 10^{-11})$$

and

$$\mu^+ \nrightarrow e^+e^+e^- \text{ (B} < 10^{-12})$$

The improvements in experimental techniques and machines cooperate to improve these observations by about an order of magnitude every 7 years. For completeness I must also list the search for rare decay modes of K mesons in "kaon factories." Pion, kaon, and B factories clearly indicate the industrialization of particle physics. The physics objectives of all of these researches are to seek out the tiny influences of presumed new physics, which is taking place at the TeV level and higher. For a mature experimenter, these are fun experiments that combine the payoff of observations (if and when) with the attention to detail of precise measurements.

Final Comments

To all of the above research I should add the new generation of structure-function research with neutrino beams, probably tagged. The 1962 two-neutrino experiment honored at this meeting has given rise to a set of activities that, in 1988, continues to play a dominating role in particle physics and its new branches, astrophysics and early universe cosmology.

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36. I regret not having the space to speak more of the accelerators, the detectors, and the people who brought these instruments into being. The Nevis cyclotron was built under the leadership of Eugene Booth and James Rainwater; work on the AGS was led by Ken Green, Ernest Courant, Stanley Livingston, and Hartland Snyder; Fermilab was under the direction of Robert Wilson and his outstanding staff. My own detector experience owes much to George Charpak of CERN and William Sippach of Columbia. In neglecting these details, I am reminded of my teacher, friend, and thesis professor, Gilberto Bernardini, who, when being shown the innards of the Nevis cyclotron, exclaimed: "Just show me where the beam comes out." Finally, I make amends to the theorists, who are crucial to the entire enterprise. I have enjoyed and profited from interactions with many theoretical physicists, but most especially T. D. Lee, M. Veltman, and J. D. Bjorken.