

ing Z particles. Within a few months, a survey of Z decays (which can go among things into a neutrino-antineutrino pair) showed that there was room in Nature for only three kinds of light neutrinos, those associated with the electron, the muon and the tau. The lid had been shut on the list of known particles.

Future

After the termination of CHARM II in the summer of 1991, CERN neutrino operations came to a halt for the first

time in 28 years. CERN's neutrino facilities have now been substantially upgraded, while preparations forge ahead for the third generation of CERN neutrino studies, with two big new experiments in the WA1/CHARM style, and together involving some 200 physicists. Upstream will be CHORUS, Klaus Winter's major Europe/Russia/Turkey/Japan collaboration using an 800 kilogram emulsion target, while NOMAD (a Europe/Russia/US/Australia collaboration with François Vannucci as spokesman) will use a magnetic spectrometer. The new CERN

neutrino beam could also serve more distant detectors, but these plans are still being discussed

The aim of CHORUS and NOMAD is to look for interactions of the third type of neutrino, that associated with the tau lepton, and to search for possible 'oscillations' between neutrino types, where a beam cyclically changes its affinity as it travels along. With the modest neutrino playing a major role in the Universe at large, these results could have a vital bearing on new ideas in astrophysics and cosmology.

Around the Neutrino Laboratories

BROOKHAVEN

Neutrino physics has been an integral part of the Brookhaven research programme for much of the Laboratory's 46-year history. Milestones have been the determination of the helicity of neutrinos (1958), the establishment of the existence of two kinds of neutrinos (1962) for which Leon Lederman, Mel Schwartz and Jack Steinberger were awarded the 1988 Nobel Physics Prize, the discovery of charmed baryons in the 7' Bubble Chamber in 1975, and the ongoing measurements by Ray Davis and collaborators of solar neutrinos, first reported in 1968.

There have also been significant contributions to the understanding of neutral currents in exclusive hadron and electron channels. In addition some of the earliest, and to date best, accelerator limits on electron-muon neutrino oscillations are from

Brookhaven experiments. The Laboratory is also the 'B' in the IMB underground experiment, built to search for proton decay and which caught neutrinos from the SN1987a supernova.

At present Brookhaven is heavily involved in the Gallex project in the Gran Sasso and recently a new collaboration has received scientific approval for a long baseline experiment to search for muon neutrino oscillations via muon neutrino disappearance.

History

In the mid-fifties a major issue was the space-time structure of the weak interaction. While it was clear that the interaction had to be either scalar/tensor or vector/axial-vector, there was conflicting evidence for either hypothesis. In preparing for an invited talk on beta decay, Maurice Goldhaber realized that not only would a measurement of the neutrino

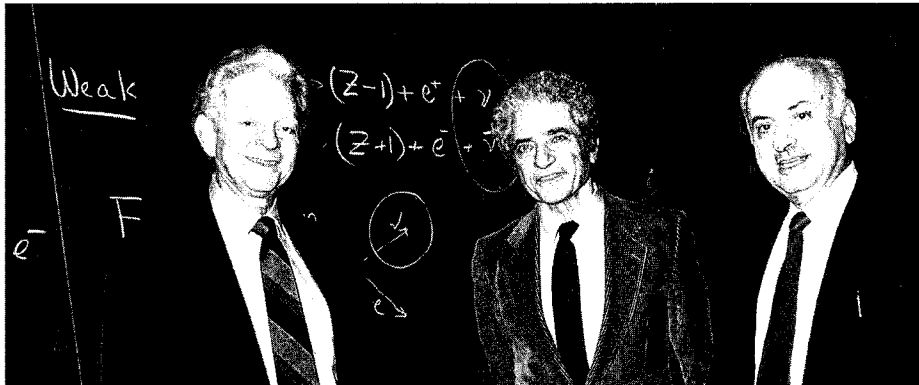
helicity (spin direction) clearly differentiate between the two hypotheses but also that there was an isotope of europium which had the required properties for the proposed measurement. This classic experiment, carried out by M. Goldhaber, L. Grodzins and A.W. Sunyar on a laboratory bench in an old army barracks in the fall of 1957, took less than two weeks from conception to completion and showed the validity of the vector/axial-vector picture.

Another issue at the time was whether the neutrinos from beta decay and pion decay were different. The non-observation of the decay of the muon into an electron and a photon led G. Feinberg, then at Brookhaven, and T.D. Lee and C.N. Yang to suggest the existence of two distinct neutrinos.

The experimental verification came from the first neutrino experiment at Brookhaven's Alternating Gradient Synchrotron (AGS) accelerator, commissioned in 1960. The basis for

Leon Lederman (left), Mel Schwartz (right) and Jack Steinberger were awarded the 1988 Nobel Physics Prize for their 1962 experiment at Brookhaven which showed that neutrinos come in more than one kind.

Cont'd page 21



this experiment was when Mel Schwartz saw that, with the weak interaction increasing with energy, then despite the relatively small yield of neutrinos at an accelerator compared to a reactor it should be possible with a large detector to detect neutrino interactions at an accelerator.

The proposal was to create a neutrino beam from the decay of pions and kaons produced from an internal AGS target. The outcome (see page 4) was that the neutrinos of pion decay are intrinsically different to the neutrinos of beta decay.

The advent of neutral currents and charm particles brought the next phase of accelerator-based neutrino activity. All the subsequent Brookhaven experiments used a new fast extracted beamline, commissioned in 1973. The beam was extracted in one turn by a fast kicker and transported to the neutrino target. The 8° bend in the transport was accomplished using the first superconducting magnet installed in an accelerator complex. The particles from the target were focussed by a magnetic horn system developed by Bob Palmer and allowed to decay in a 50 metre tunnel. The resulting wide band beam peaked near 1 GeV and had a long tail with approxi-

mately 10% above 4 GeV. Essentially unmodified, this beam was Brookhaven's neutrino source for well over a decade. Intensity and reliability have increased steadily to the point where, once the new Booster is fully operational, it will be possible to produce some 6×10^{13} protons on target every 1.5 sec. This high rate with the associated timing structure is at the heart of all present planning for continuing neutrino physics at Brookhaven.

The beam was originally designed for use with the 7' cryogenic bubble chamber, built by Ralph Shutt's group, which first took data in 1974. The first hydrogen exposure of the chamber showed a charged current event with a lambda decay and a number of soft charged tracks.

After six months of painstaking work a Brookhaven group led by Nick Samios concluded that there were no missing neutrals and that all the charged tracks, apart from the muon, were pions. This implied that a hitherto classic selection rule had been violated and the event was the production of a charm particle - the first observation of 'open' charm. The c-suffix nomenclature for charmed baryons introduced in these papers went on to become standard.

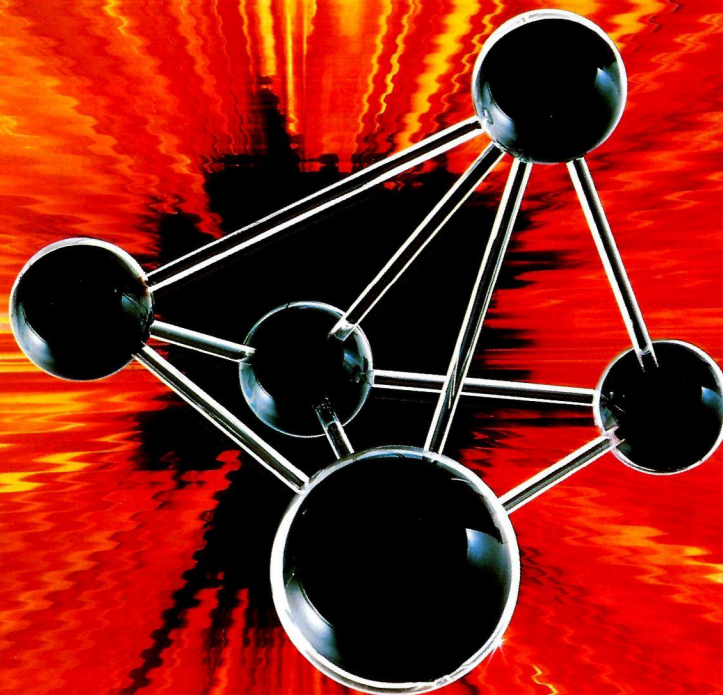
The Brookhaven Bubble Chamber

group headed by Samios and Palmer together with the Columbia group led by Charles Baltay were also working during this period on E53 at Fermilab. This heavy liquid experiment in the Fermilab 15' bubble chamber measured neutrino-electron elastic scattering and produced significant results on the strange particle content of opposite sign dilepton events, helping to establish that charm production was the source.

Not long after the Brookhaven beamline became operational, two electronic experiments began looking at exclusive hadronic neutral current interactions; E605, a Brookhaven/Columbia/Illinois/Rockefeller collaboration led by W. Lee, used an optical spark chamber while E613, a Brookhaven/Harvard/Pennsylvania/Wisconsin collaboration with L. Sulak and H.H. Williams as spokesmen, used a large segmented liquid scintillator detector.

The success of E613 led to a much more ambitious liquid scintillator project - E734 - a major US-Japan collaboration led by R. Lanou, A.K. Mann, Y. Nagashima and D.H. White and eventually involving Brookhaven, Brown, Hiroshima, KEK, Osaka and SUNY Stony Brook. The initial goal was to measure the elastic scattering of neutrinos and antineutrinos on electrons and protons. The 150 ton main detector had segmented planes of liquid scintillator followed by proportional drift tubes. As well as determining the weak mixing angle, this measurement was also sensitive to the strange quark content of the proton.

E734 also provided one of the earliest limits on the mixing angle in muon-electron neutrino oscillations, and since the detector was close to the neutrino source the limit has survived. Recently a dedicated



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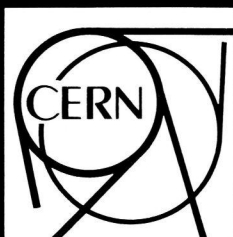
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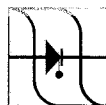
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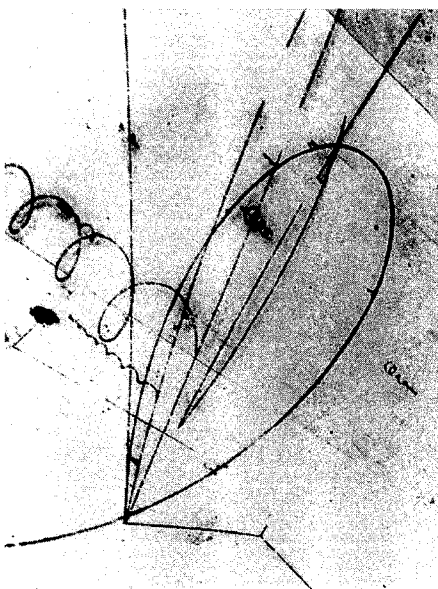
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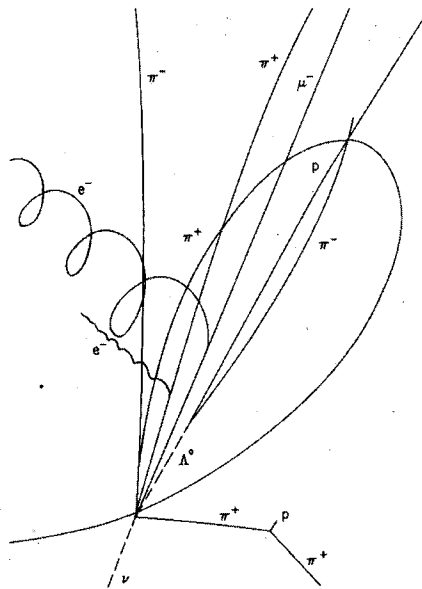
Charm comes out into the open. Photograph from Brookhaven's 7' cryogenic bubble chamber showing a charged current event with a lambda decay and six charged pion tracks.



neutrino oscillation experiment, E776, a Columbia/John's Hopkins/Illinois collaboration with W. Lee as spokesman, in the same beam but located at 1 km, significantly improved the mass limit for large mixing angles.

The solar neutrino problem is still one of the most intriguing unresolved problems in physics. While it is clear that the sun is a copious source of neutrinos, it was only in the late 1950s with W.A. Fowler's conjecture that the solar cycle could be expected to produce boron-8 with its high energy decay neutrino that it seemed experimentally feasible to detect solar neutrinos.

A number of potential detectors were discussed and some test modules built. The immediate outcome was the Brookhaven Chemistry Department chlorine experiment led by Ray Davis. This large tank of chlorine-rich cleaning fluid has been active in the Homestake gold mine in Lead, South Dakota now for close to 30 years. The original projections were that the total solar neutrino capture rate in 520 metric tons of chlorine would be 2 to 7 per day.



Solar neutrino capture produces argon-37 atoms which can be extracted and counted in a small proportional counter with very low noise electronics, developed in Brookhaven's Instrumentation Division.

The original 1968 paper only gave an upper limit on the solar neutrino flux from boron-8 as the observed rate was consistent with the background rate from the counter. However more data, more sophisticated analysis methods, and improvements in electronics led to a definite determination of the flux.

While the accumulated data over the past years has sometimes led to conjectures about solar cycles or other phenomena, the observed rate has been consistently less than solar model predictions.

Brookhaven is a member of the IMB collaboration which in 1979 proposed to search for proton decay in a large water Cherenkov detector. By 1983 they had already established that the proton lifetime was much longer than predicted by the minimal grand unification model.

In the course of refining these limits,

the collaboration have extended their mandate, covering also extraterrestrial neutrinos, and making two important measurements. In 1987 they observed 8 neutrino events resulting from the SN1987A super-nova explosion and recently have noted an inconsistency between the calculated and observed ratio for atmospheric muon and electron neutrinos.

Brookhaven's solar neutrino tradition is extended with the new Gallex experiment in the Italian Gran Sasso Laboratory which sees neutrinos from the primary solar proton-proton interaction. The IMB group will also participate in the Japanese Super-kamiokande project (see page 32).

A new collaboration - Brookhaven, UC Santa Barbara, Linfield College, Los Alamos, New Mexico, Pennsylvania, Southern, Temple, TRIUMF, and Valparaiso - has recently had scientific approval for a major new initiative on neutrino oscillations. The aim is to search for muon neutrino oscillations via muon neutrino disappearance with emphasis on small mass differences. The goal is to cover the region allowed by the anomalies in the atmospheric neutrino rates recently reported by both Kamiokande and IMB with three detectors, the furthest being at least 20 km from the neutrino target.

Brookhaven has had a long and profitable association with the neutrino, with experiments which have contributed greatly to our understanding of the neutrino itself, to the evolution and validation of weak interactions and the Standard Model and which have exploited the neutrino as a probe of rare phenomena. With a major new experiment being prepared, the Laboratory's strong neutrino tradition lives on.

Wide and narrow bands

Getting neutrino beams is all about getting enough parent particles. The pioneer neutrino experiments at Brookhaven in 1962 used no focusing tricks, however the invention of the magnetic horn by Simon van der Meer at CERN enabled a wide range of parent kaon or pion momenta to be concentrated into a cone, boosting the subsequent neutrino yield in a 'wide band beam'. The focusing horn also selects the electric charge of the pions and kaons, thereby determining whether neutrinos or anti-neutrinos are obtained. However there is little indication of what the energies of these neutrinos (or antineutrinos) are.

Another approach is the 'narrow band beam', where a limited range of parent pion or kaon momenta is selected, giving a forward peak. Here the offset of the neutrinos from the forward direction gives an indication of their energy. However as pions and kaons decay in different ways, the resultant neutrino beam covers two (narrow) momentum bands, and is 'dichromatic'. The first such beams were used at Fermilab in the early 1970s.

The Fermilab 'flagship' E1A neutrino experiment pioneered the use of large neutrino calorimeters. In this 1973 photo are, left to right, standing, Alfred Mann, Richard Imley, David Cline, T.Y. Ling, Don Reeder, Jim Pilcher and Bernard Aubert; seated, Carlo Rubbia, Karen Mattison and Fred Messing.

FERMILAB

Neutrino experimentation at higher energies was among the justifications for the construction of Fermilab and the earliest studies utilized these new beams produced with 350-400 GeV protons. This pre-Tevatron period used both electronic counters and the new 15-foot cryogenic bubble chamber.

The counter experimental programme was basically divided into two generations. The first covered the discovery of new phenomena and confirmation of the parton model using high rate wide-band and the first dichromatic narrow-band neutrino beams. The second concentrated on precision measurements with dichromatic beams.

One flagship experiment, designated "E1A", was originally a collaboration of Harvard, Pennsylvania and Wisconsin, and was the prototype of large neutrino calorimeters: a target/calorimeter followed by a large set of iron toroidal magnets. E1A and its successor, E310 (which included

Rutgers), ran for a total of 6,650 hours from 1972 through 1978. Contemporary with these experiments was another large counter experiment by CalTech and Fermilab, designated originally as E21A. Along with its successors, E262, E320, and E356 (which collected data over some 4,600h) it took part in the first generation programme, and subsequently spearheaded the second generation with precision measurements of both charged current structure functions and the weak mixing angle. Finally, this latter collaboration extended its participation into the early Tevatron era, and will continue through the 1990s.

The E1A-inspired programme ended with E310 and a dedicated low-mass, highly visible counter neutrino experiment, E594 took its place. E616 plus E594 constituted the second generation of pre-Tevatron Fermilab experiments.

The Fermilab "15-foot" bubble chamber (actually, a 12 foot diameter sphere with a 3 foot upstream nose), began operation in 1973, with a neon-hydrogen mixture exposed to

