

Neutrinos at CERN

As Head of Nuclear Physics Apparatus Division in the early 1960s, Colin Ramm played a major role in launching CERN's programme of neutrino experiments.

CERN's long and distinguished neutrino tradition began in 1958 at the then new 500 MeV synchrocyclotron (SC) with the first observation of the decay of a charged pion into an electron and a neutrino.

At that time, the first ideas on the special (vector/axial vector) structure of the weak interactions had been put forward by Feynman and Gell-Mann and by Marshak and Sudarshan, but the continual non-observation of that charged pion decay was holding up progress.

This decay is only one part in ten thousand, and is masked by the dominant muon-neutrino channel. A special telescope was built to pick up the high energy electrons from the pion decay. In 1962 came another SC neutrino success, with the first measurement of the decay of a charged pion into a neutral one, with emission of an electron and a neutrino.

Meanwhile the main thrust of CERN's neutrino effort was taking shape at the PS. By the close of 1960, CERN had decided to attack neutrino physics using several detectors - a 1m heavy liquid bubble chamber from André Lagarrigue's team in Paris, a CERN 1 m heavy liquid bubble chamber, and a hybrid chamber/counter from a group led by Helmut Faissner.

In 1961 work on this experimental programme was abruptly terminated when it was realized that the available neutrino beam would not provide enough particles for the detectors being planned. Brookhaven stole the thunder and discovered muon neutrinos (see page 13).

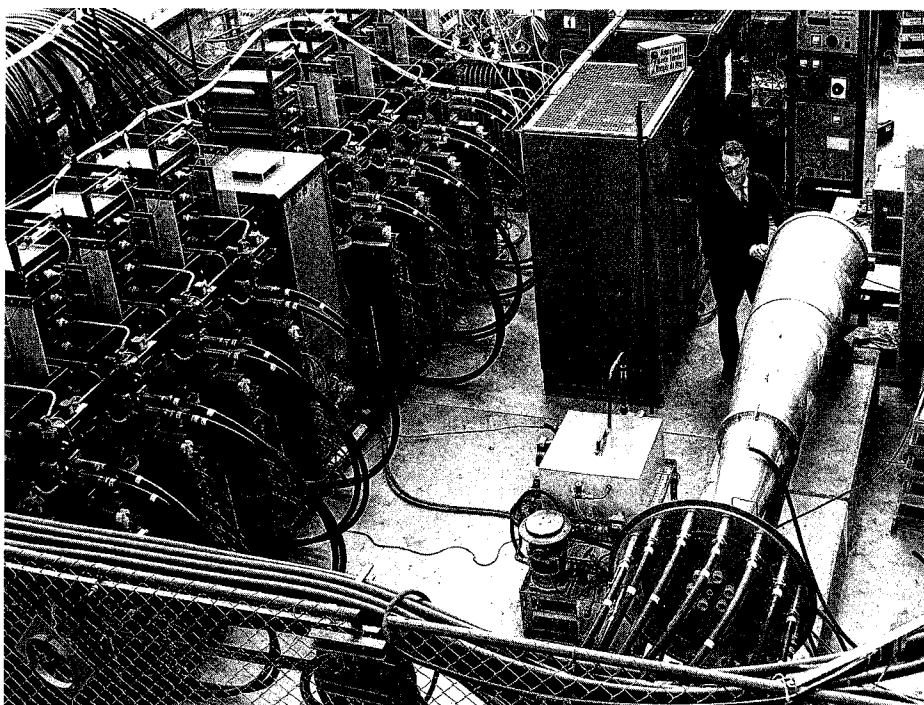
CERN abandoned its initial idea of several smaller detectors and plumped instead for a big spark chamber, mounted in series with Colin Ramm's 1-metre heavy liquid bubble chamber. (Neutrino interac-



tions are so few and far between that a neutrino beam can be fired through a series of targets, lined up one after the other.)

To boost the PS neutrino supply, new focusing techniques - the famous 'magnetic horn' - were developed by Simon van der Meer, with beams of charged pions and kaons being concentrated in the decay region to boost the neutrino supply. Crucial to this idea was the fast ejection system developed in 1959 to rip particles from the PS beams.

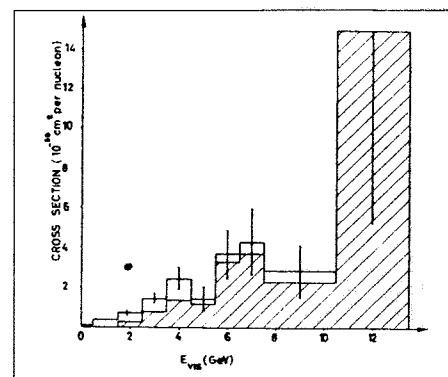
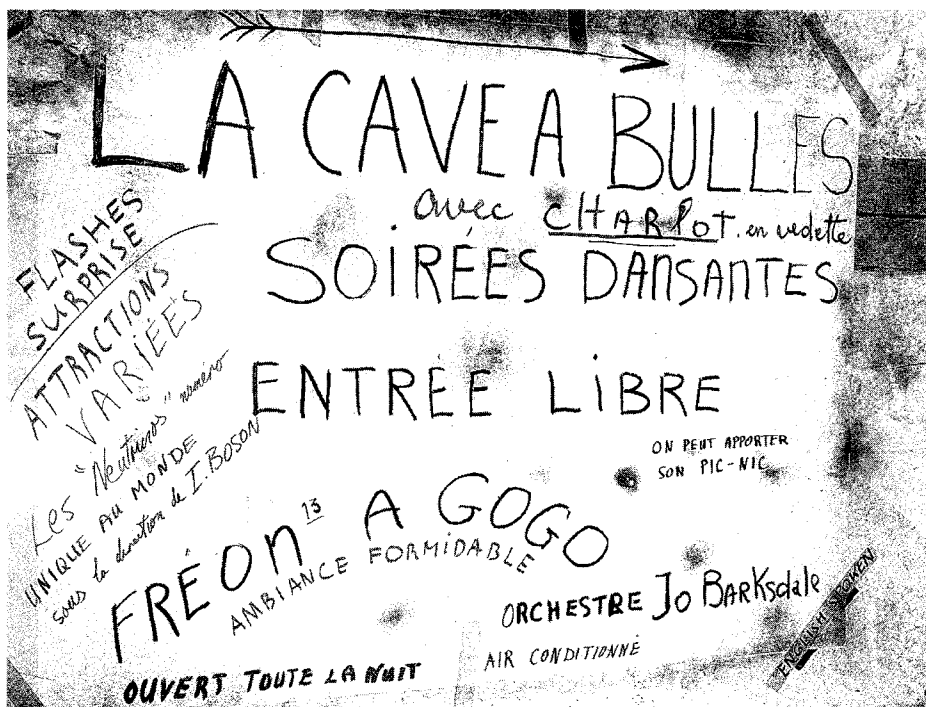
Although CERN had a machine to rival Brookhaven, it was clear that in 1961 CERN detector expertise was lacking. Neutrinos needed massive detectors on a scale never seen before, and such a major programme had not been foreseen. In 1961 CERN's Director General John Adams said 'there is no group with sufficient staff for such a project and



Simon van der Meer's famous magnetic horn increased the intensity of the parent beams and made for more neutrinos. (Photo CERN 317.1.63)

Graffiti were still rudimentary when CERN's neutrino programme got underway.

More writing on the wall. 1964 - evidence for the increasing reaction rate (cross-section) of neutrinos.



committed and clinched the vital discovery.

Ten years before, at the modest start of the CERN neutrino programme, bubble chamber work had seen that neutrino interaction rates increased with energy. Some far-sighted people had been intrigued, but at the time there were no explanations on the market.

At the end of the 1960s, experiments at Stanford with high energy electron beams showed that small scattering centres - 'partons' - carrying half a unit of spin were hidden deep inside the proton. What was the electric charge of these partons? In 1972, just before the neutral current discovery, experimental results from several directions and new theoretical analysis converged. The striking similarity of nucleon structure seen at Stanford using electrons and at CERN using neutrinos and antineutrinos confirmed that the dynamic scattering centres, the partons, could be identified with the static quark building blocks, carrying fractional electric charge, which explained particle spectroscopy.

In particular, the neutrino interaction rate seen in Gargamelle was approximately three times that of anti-neutrinos. In 1969 theorists David Gross and Christopher Llewellyn Smith showed how this factor of three is explained by neutrino scattering off the three valence quarks of

there is no budget for such a major piece of equipment.'

The lesson learned, the necessary investment was made and CERN's neutrino programme pushed ahead with new vigour, beginning in earnest in 1963.

To increase the particle supply after its modest start, CERN authorized a 1 GeV 'Booster' synchrotron, while a major project in France for a huge heavy liquid bubble chamber was expedited, capitalizing on André Lagarrigue's initial experience with a 1-m design. The outcome, the Gargamelle chamber, 4.8 metres long, containing 18 tonnes of freon, and with infrastructure weighing 1000 tonnes, was initially installed at the 28 GeV PS proton synchrotron, coming into operation at the end of 1970.

Before 1973, weak interactions had only been seen to operate through a 'charged current', where electric charges get swapped around. In contrast, in neutral current interac-

tions, the neutrino sets other particles in motion without changing charges. Such neutral currents had been predicted by the 1967 electroweak unification of electromagnetism and the weak force by Sheldon Glashow, Abdus Salam and Steven Weinberg, but had never been seen. In 1971 Weinberg had taken another look at the neutral current prediction and saw that the effects would anyway be very small. The experiments had not looked hard enough.

In 1973 came the big pay-off for Gargamelle and CERN - the discovery of neutral currents, the first new type of physics interaction to be seen for forty years.

In the face of intense competition from across the Atlantic and with post-war European physicists unused to running at the front, European confidence in the Gargamelle result had occasionally wavered. But thanks to the perseverance of its strong personalities, the bubble chamber team remained totally

In the mid-70s, CERN's new SPS proton synchrotron featured two major all-electronic neutrino experiments. WA1 (a CERN/Dortmund/Heidelberg/Saclay collaboration) used a 20-metre long, 1500-ton array of neutrino-catching iron-cored toroidal magnets interspersed with drift chambers and scintillation counters...
(Photo CERN 1.10.76)

e nucleon, each carrying half a unit spin.

Gargamelle also showed that there was room inside nucleons for something else other than quarks. It was an early hint that nucleons could also contain gluons, the carriers of the inter-quark force

Higher energies - the SPS era

With neutrino interactions now on a much firmer footing, the next quest was to understand the structure of the new weak interaction.

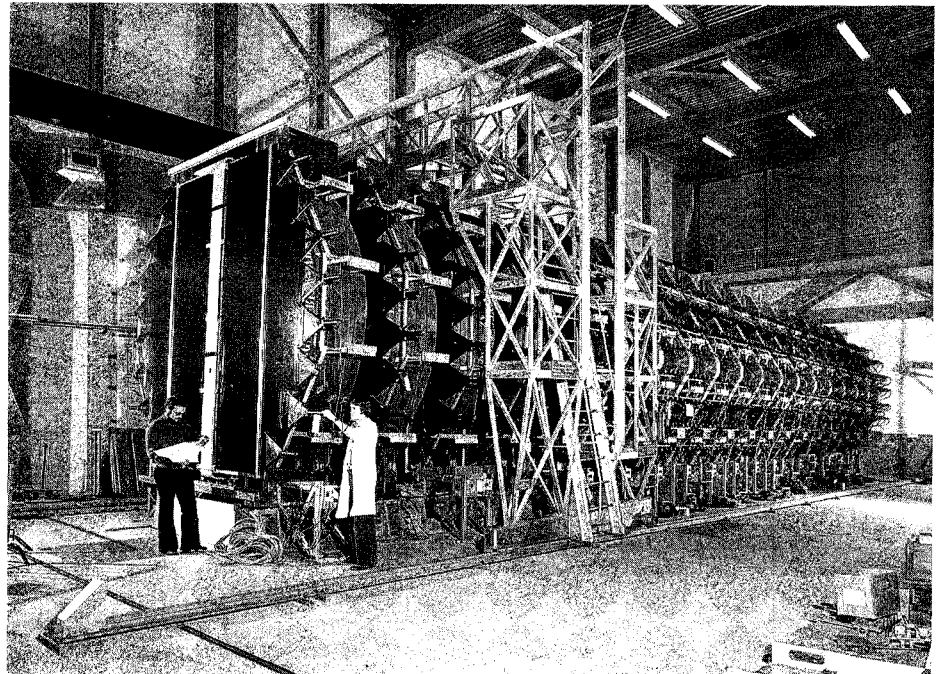
Fermilab in the US had started to explore a new field of higher energy neutrino physics in 1972 (see page 1).

In 1977, CERN's new SPS 450 GeV proton synchrotron came into operation, armed with an impressive array of four major neutrino detectors lined up one after another in the beam line.

The Gargamelle bubble chamber, hoping to add new jewels to its neutral current crown, had been resited for the new beams, but unfortunately was forced to retire the following year when its tired chamber cracked from metal fatigue.

The 3.7-metre diameter 'Big European Bubble Chamber' (BEBC), commissioned in 1973 with hydrogen filling for hadron work, added to its repertoire a heavier neon-hydrogen filling for SPS neutrino studies. It was also fitted with an outer wire chamber 'ence' for muon detection.

Sandwiched between the two big bubble chambers in the SPS West area were two major new all-electronic detectors. Jack Steinberger's WA1 CERN/Dortmund/Heidelberg/Saclay group used a 20-metre long, 1500-ton array of neutrino-catching iron-cored toroidal magnets interspersed with drift chambers and scintillation counters. Immediately



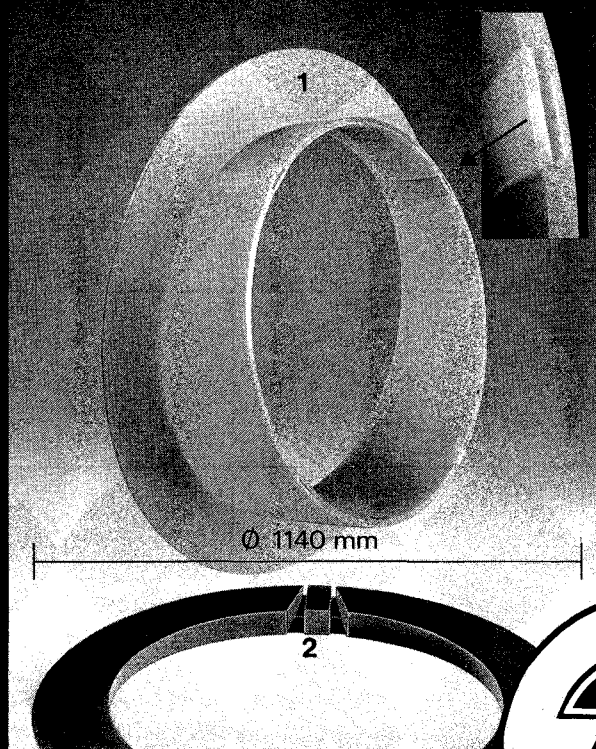
downstream of WA1 was Klaus Winter's 'CHARM' (CERN/Hamburg/Amsterdam/Rome/Moscow) collaboration, with a substantial and fine-grained target calorimeter preceding a magnetized iron calorimeter. Together, WA1 and CHARM occupied nearly 40 metres of experimental hall. Although they were separate experiments, they occasionally combined forces for joint studies.

For eight years, these big detectors made precision studies on the structure of the charged and neutral currents of the weak interaction. In contrast with early neutrino studies which were happy to collect handfuls of events, these big detectors recorded millions. While the charged current is left-handed, the weak current has both right- and left-handed behaviour, and pinning down this 'handedness' was vital to understanding the underlying theory. A thorough study of multimMuon final states gave valuable information on the production of the fourth ('charm') quark, showing how this new quark

played a vital role. In addition neutrino interactions deep inside target protons and neutrons probed the underlying quark field theory - 'quantum chromodynamics'.

Having several detectors in series enabled physicists to compare upstream and downstream neutrino signals and gave authoritative new limits on neutrino oscillations.

By 1985, CHARM had given way to CHARM II, a 700-ton array of glass plates interspersed with scintillator and streamer tubes and a downstream muon spectrometer. CHARM II collected several thousand examples of the rare but very clean scattering of neutrinos off electrons, providing precision information on the neutral current mediating these interactions, and showing that the axial-vector part of the electron coupling (the difference between its right- and left-handed behaviour) is -0.5, in agreement with the underlying symmetry picture, where the electron and its neutrino are paired with the 'up' and 'down' quarks.



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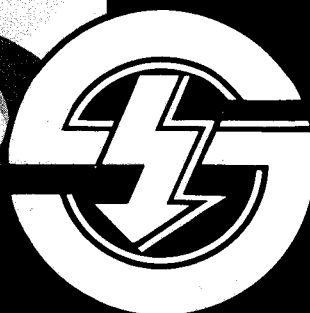
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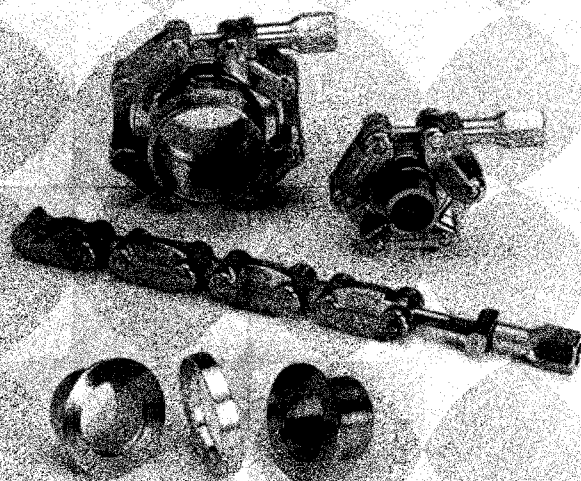
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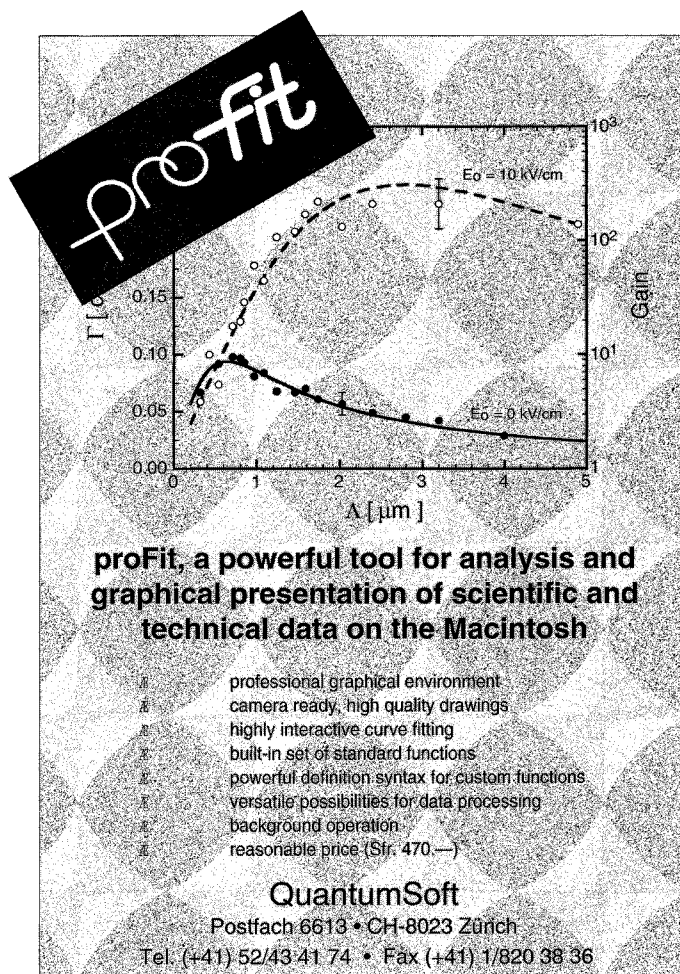
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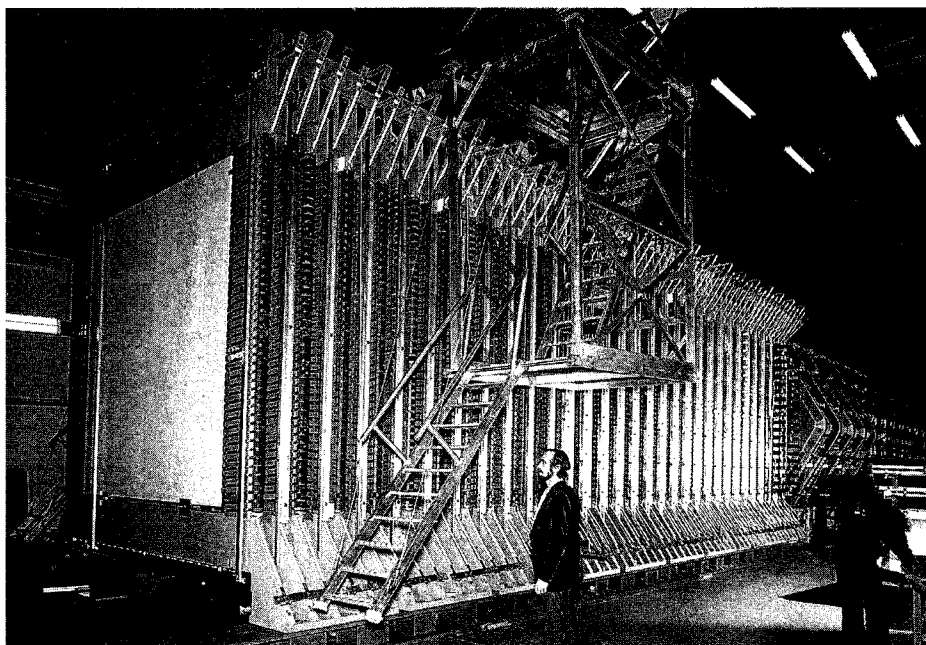
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Downstream of WA1 (just visible on the right) was the big 'CHARM' (CERN/Hamburg/Amsterdam/Rome/Moscow) detector, with a substantial and fine-grained target calorimeter preceding a magnetized iron calorimeter. Together, WA1 and CHARM occupied nearly 40 metres of experimental hall. (Photo CERN 213.12.77)



The electroweak picture

The big new high energy neutrino experiments had also made the first precision measurements of the electroweak parameters. For the first time, the hunters of the W and Z bosons, the particles carrying respectively the charged and neutral currents of the weak interactions, knew exactly where to look. In 1983, the big experiments at CERN's proton-antiproton collider discovered the W and Z bosons just where they were expected.

It was a triumph for the W and Z hunters, for the underlying theory, and all the preparatory studies. The electroweak picture was ready for the textbooks.

Next year, CERN's big third generation neutrino experiments -NOMAD and CHORUS - will open a new chapter in this area of science. Seen here is the muon spectrometer of CHORUS, with, to the right, its calorimeter (drawn back) and the box housing among other things the emulsion target. (Photo CERN EX 44.7.93)

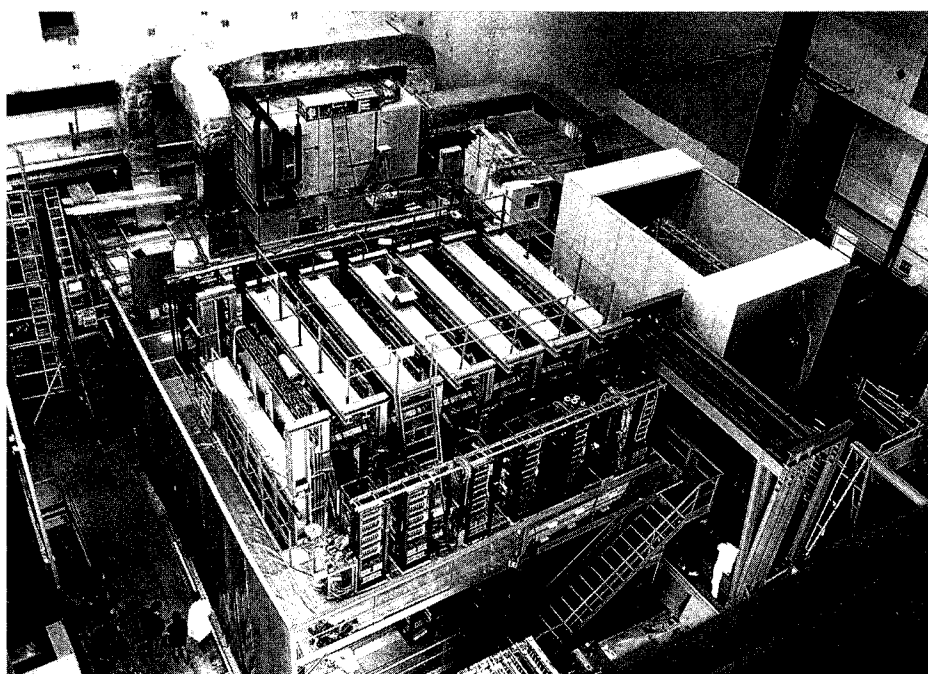
The high energy information from these collider experiments was also a perfect complement to the lower energy studies using neutrino beams, giving a wide reach on the consist-

ency of the electroweak unification which is still quoted today.

While the big UA1 and UA2 experiments at the proton-antiproton collider did not explicitly catch neutrinos, they pioneered the 'missing energy' technique for showing where neutrinos had been. Even conventional particles can sometimes 'disappear' down cracks between detector components. UA1 and UA2 made sure that all such cracks in the detector screen were firmly covered. Outgoing energies on two opposite sides of the detector were added up, and any mismatch showed where energy had been carried off by particles, such as neutrinos, which had passed right through the detector.

In this way they could see, for example, the tell-tale coincidence between an electron and a neutrino coming from the decay of a W.

In 1989, CERN's LEP electron-positron collider began mass-produc-



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