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STUDIES IN CERN HISTORY

EXPERIMENTAL STUDIES OF WEAK INTERACTIONS

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Experimental studies of weak interactions

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EXPERIMENTAL STUDIES OF WEAK INTERACTIONS

I. Introduction

The previous period of 1960-1965 (volume II) was marked by important contributions of CERN to the understanding of the weak interaction. We recall them very briefly. There was the discovery of the pion decay into an electron and a neutrino of the SC and a measurement of its rate [1]. Before, the V-A theory of the weak interaction had been in difficulty because earlier experimental results had failed to show the existence of that decay mode with the predicted branching ratio of $1.2 \cdot 10^{-4}$. Thus, this important experiment can be considered as the corner stone of our understanding of the V-A interaction.

A further important experiment, also performed at the SC, made the first observation of the pion beta decay, $\pi^+ \rightarrow \pi^0 e^+ \nu$ [2], and measured a branching ratio of $\sim 10^{-8}$.

The corresponding decay rate could be predicted theoretically from the measured rate of the super-allowed beta-decay $O^{14} \rightarrow N^{14} e^+ \nu$ using the hypothesis of the conserved vector current (CVC). This was the first step towards a full theoretical understanding of the weak hadronic current. The next step came with the notion of quark mixing from Cabibbo and later from Kobayashi and Maskawa. In the period from 1966-1980 a series of beautiful experiments on hyperon and kaon decays was conducted at CERN which, through its high precision results, established the validity of the quark mixing scheme.

Another important confirmation of the V-A theory had come through a measurement of the helicity of the muon resulting from $\pi \rightarrow \mu \nu$ decay [3] at the PS. It was based on the measurement of the helicity asymmetry in the scattering of muons on electrons in magnetized iron.

In 1964 the success of the V-A theory with its exact CP symmetry was shaken with the discovery of the unexpected decay $K_L^0 \rightarrow 2\pi$. This decay mode is not allowed if CP invariance is exact. Its observation at Brookhaven [4] thus showed that our understanding of the weak interaction was not complete (figure 1.1). In particular, the smallness of this violation ($2 \cdot 10^{-3}$) compared to maximal violation of parity and charge conjugation invariance was difficult to understand.

An intense experimental activity started on the study of CP violation effects, in which CERN played an important role. Initially, a number of suggestions had been made which allowed to avoid the conclusion of CP violation. Among them was the possibility of a long-range cosmological vector field which would introduce a small $K^0 - \bar{K}^0$ mass difference. The resulting strong energy dependence of the decay rate ($K_L^0 \rightarrow 2\pi$) was however not found experimentally [5]. The beautiful and precise experiments at CERN (1966-1980) which were of key importance for the phenomenological analysis of $K^0 \rightarrow 2\pi$ decay led to the important conclusion that CP violation was accompanied by a violation of time reversal invariance T

by an amount compatible with CPT invariance, whereas CPT violation was ruled out. Experimental studies which aim at understanding the origin of CP violation continue at CERN to the present day [6]. By measuring with high precision the double ratio

$$\frac{\Gamma(K_L^0 \rightarrow 2\pi^0)/\Gamma(K_L^0 \rightarrow \pi^+\pi^-)}{\Gamma(K_S^0 \rightarrow 2\pi^0)/\Gamma(K_S^0 \rightarrow \pi^+\pi^-)}$$

they have detected a direct CP violation in the decay amplitude at the three standard deviation level. This important result indicates that CP violation may be induced by the Cabibbo-Kobayashi-Maskawa quark mixing matrix and would give a natural explanation of the smallness of the violation in terms of a product of three small mixing angles and a CP violating phase angle. However, this result requires further experimental confirmation and a new experiment is under construction at CERN [7] which can reduce the error by an order of magnitude.

Figure 1.1 Cartoon shown by N. Cabibbo at the 1966 Int. Conf. on High-Energy Physics, Berkeley : Where we stand [112].

The most important part of the weak interaction work at CERN were the neutrino physics programmes. While a first attempt to compete with Brookhaven, in searching for the second neutrino flavour, the muon neutrino, had not led to a success, the great results achieved at CERN in the period 1966–1980, under consideration here, were the result of careful planning and of efforts consistently pursued over many years. The first successful intense neutrino beam at CERN, built in 1961–63 under the leadership of Colin Ramm, used the new techniques of ejecting the PS proton beam onto an external target and of focussing positive or negative beams of pions and kaons towards the decay region and the detectors by a new device, the magnetic horn invented by Simon van der Meer [8].

At the PS these plans involved the increase of the PS intensity through the addition of the booster and the construction of a high quality neutrino beam with a compact iron shield. The first series of neutrino experiments had

demonstrated the superiority of heavy liquid bubble chambers. It was therefore decided to build a very large heavy liquid bubble chamber in France following a proposal by A. Lagarrigue, P. Musset and A. Rousset. This chamber was installed at CERN and started data taking in 1971. Figure 1.2 shows a photograph of Gargamelle and its environment.

The results obtained with Gargamelle at the PS are well known [9]. The most prominent result is the discovery of weak interactions of the neutral current type. The first evidence for this new phenomenon came from the observation of one event of antimuon neutrino-electron scattering in 1973. Soon after, the experiment gave evidence for the existence of neutral current interactions in neutrino-nucleon processes. Not since the early thirties had a new type of fundamental force been discovered. A unified gauge theory of weak and electromagnetic interactions with spontaneous symmetry breaking had been proposed independently by Weinberg and Salam in 1967-68, following earlier pioneering work by Schwinger and Glashow. When its renormalisability was proved by 'tHooft in 1971 it was an extremely attractive theory of the weak interactions. Neutral current weak interactions are an intimate part of this theory and a sizeable effect had to be seen in neutrino processes. There they were discovered by Gargamelle in 1973. Experiments with Gargamelle achieved several other important results. Among them is the observation of a linear rise of the total neutrino-nucleon cross section [10]; it revealed the point-like nature of the nucleon constituents involved in high energy neutrino reactions. Later it was shown that these constituents can be identified with the quarks and antiquarks, and their momentum distribution could be determined from deep inelastic neutrino scattering.

Figure 1.2 The Gargamelle Bubble Chamber at CERN [47].

(a) plan of the Chamber.

(b) schematic view of the installation.

A spark chamber set-up built by an Aachen-Padova collaboration was added in this beam line in 1972 and made a pioneering attempt to study neutrino-electron scattering.

A new programme with a neutrino facility of very high quality was planned at the SPS. It again involved a neutrino beam of the wide energy band type successfully developed at the PS and in addition a new type, a so-called narrow band beam, with parents of selected momentum in a narrow momentum band. This new type of beam provided an important new tool for the continued study of the quark structure of nucleons in deep inelastic neutrino scattering and for detailed experiments on the Lorentz and isospin structure of the neutral weak interaction. Despite its late start in 1977 compared to the start in 1972 of an accelerator of similar energy at Fermi National Laboratory near Chicago, the 400 GeV SPS neutrino programme made almost immediately a very strong impact. The SPS neutrino beam line in the West Area is an impressive installation. It emerges at an angle of 42 mrad from the underground target area and crossed successively several detectors, first BEBC, the Big European Bubble Chamber filled either with hydrogen, deuterium or with a neon-hydrogen mixture, the massive electronic detector of WA1 designed mainly for the study of deep inelastic neutrino scattering by weak charged current processes, the fine-grained electronic detector of WA18 aimed at a detailed study of weak neutral current processes and until 1978 (when it sprang a leak due to material fatigue) the Gargamelle bubble chamber. Later, in 1985, the new electronic detector of WA79 replaced the other two electronic detectors. Its design aimed at a precise study of neutrino-electron scattering.

The next step of verifying the unified theory of the electroweak interaction was a search for the weak intermediate bosons. Measurements of the electroweak mixing parameter $\sin^2\Theta_W$ in neutrino induced neutral current processes led to predictions of m_W and m_Z in the 80-90 GeV mass range. Here again, through important technical advances in the stochastic cooling concept invented by Simon van der Meer [11] and in its use for an antiproton accumulator and $\bar{p}p$ collider in the SPS ring conceived by Cline, McIntyre and Rubbia [12], and careful planning, CERN has achieved a high quality physics facility which led to the discovery of the intermediate bosons W and Z in 1983. The advances in detector concepts and techniques which led to their discovery by the UA1 and UA2 experiments are unrevocably linked to this great success [13].

With the discovery of the weak neutral current interaction and the intermediate bosons CERN has led the field of elementary particle physics to the next step, the large e^+e^- collider LEP operating at CERN since 1989 at the Z^0 pole. At this installation the unified theory is being put to a series of high precision tests.

The existence of the hypothetical Higgs boson which induces the spontaneous symmetry breaking is being searched for at LEP and has not been detected at the time of writing. If its mass would be larger than 80 GeV this search may have to be pursued at the LHC, CERN's next large research facility, a 15 TeV pp collider to be added in the LEP tunnel in 1998.

II. Neutrino Physics

II.1 Discovery of the weak neutral current interaction

In 1973 a new weak interaction induced by neutral currents was discovered at CERN in neutrino processes in Gargamelle. The story of this discovery has been told in detail by P. Galison [14]. One event of elastic scattering of antimuon neutrino on an electron was found at Aachen in early 1973 [15] and evidence was growing of neutrino-like interactions without a muon or electron. While the $\bar{\nu}_\mu e$ event was unambiguous (see figure 2.1) because of the spiralling electron which recoiled at a small angle with respect to the neutrino beam direction, the interpretation of the hadronic events of the type

$$\nu(\bar{\nu})N \rightarrow \nu(\bar{\nu}) + \text{hadrons}$$

was more difficult because of the neutron background created by neutrino interactions in the body of the bubble chamber. The main challenge of the experiment was to show that the muonless events were not due to stray neutrons. This demonstration was difficult because the lateral dimensions of the chamber were not much larger than the neutron mean free path in the freon filling it. However, after nearly a year of painful work and long discussions, the neutron background could be separated from neutrino induced muonless events, because of the energy difference of neutrino and neutron induced events and by the uniform distribution of neutrino events along the chamber whereas the neutron events decrease exponentially along the axis of the chamber as expected for the neutron mean free path in freon (see figure 2.2) [16]. Not everyone was convinced by this evidence; Jack Steinberger [17] wrote in his Nobel lecture :

'I myself was a sceptic for a long time, and I lost a bottle or two of good wine on this matter.'

Confirmation came slowly, initially in a controversial way, from the electronic experiment E1A of Cline, Mann, Rubbia and co-workers at Fermi National

Figure 2.1 A candidate for $\bar{\nu}_\mu e$ scattering found in Gargamelle in 1973 [47].

Laboratory. Despite the considerable advantage of ten times higher neutrino beam energy the discrimination of pions and muons was difficult and led to some uncertainty in the fraction of muonless events with respect to variations of the fiducial volume.

Finally, in March 1974 the Fermilab Collaboration published new evidence in convincing form [18]. Weak neutral currents were here to stay. The neutral current interaction was thought to be mediated by a neutral boson, the Z^0 . Unfortunately, this very important discovery has remained unrewarded by a Nobel prize because of the untimely disappearance of Andre Lagarrigue (1924-1974).

What previously had been considered a weakness and a handicap of the work at CERN, the multinational collaboration of many university groups (Aachen, Brussels, Ecole Polytechnique Paris, Milano, Orsay, University College London) with CERN, turned into a triumph. While Viktor F. Weisskopf wrote in his biography, *The Joy of Insight* [19] :

'much was accomplished during my tenure at CERN, but more could have been done. Because the European scientists were acquiring experience so slowly, we were prevented from fully exploiting the possibilities offered by the new equipment'

about the period preceding the discovery of neutral currents at CERN, the careful planning and the superiority of the neutrino beams and the detectors at CERN together with the new 'style' of international collaboration had led to a fundamental discovery.

II.2 Why did it take more than fifty years to discover weak neutral current interactions?

Neutral current interactions do not change the flavour of quarks; for this reason they remained undiscovered in decay processes because they are completely masked by electromagnetic processes in the form of gamma ray emission.

But even in neutrino reactions it took ten years to discover that there are neutral current reactions at the level of 30% of the charged current processes. This is also reflected by the poor showing of a search for neutral currents in the list of priority of Gargamelle [14]. There were two reasons for this; one was based on the low limit placed at CERN in 1967 on strangeness-changing neutral currents [20],

$$\frac{\Gamma(K_L^0 \rightarrow \mu^+ \mu^-)}{\Gamma(K_L^0 \rightarrow \text{all})} < 1.6 \cdot 10^{-6} \quad (90\% \text{ C.L.}) ;$$

the other is based on experimental upper limits on the ratio of elastic neutrino scattering [21], $\sigma(\nu_\mu p \rightarrow \nu_\mu p) / \sigma(\nu_\mu p \rightarrow \mu^- p)$ and on the exclusive channel $\nu_\mu p$

Figure 2.2 Distribution of the origins of muonless events in Gargamelle along the neutrino beam axis, for NC candidates and for neutron stars [47].

$\Rightarrow \nu_{\mu} \pi^0 p$ [22] which were reported and seemed to exclude the phenomena predicted by the gauge theory of a unified electroweak interaction [23]. Figure 2.3 shows Gilberto Bernardini reporting in 1964 on the results of the first neutrino

Figure 2.3 G. Bernardini reporting on results from the neutrino programme at CERN (1964) (From "25 years of CERN").

experiment at CERN. On the right-hand side of the blackboard he has written the limit on neutral currents that excluded the predicted phenomena.

On the other hand, owing to the small lateral dimensions of the detectors in the first generation of neutrino experiments at accelerators as compared to the neutron mean free absorption path, and despite a persistent rumour of a "background" of events of unidentified origin, inclusive neutral current neutrino events could not be discriminated against neutron interactions, and remained uncovered.

Suddenly, in the spring of 1971, following the proof of the renormalizability of the Weinberg-Salam theory by 'tHooft [24], theoreticians and experimentalists took a new interest in neutral currents and calculated experimental consequences of the theory. Glashow, Iliopoulos and Maiani postulated in 1970 [25] a mechanism invoking a fourth quark (charm) to suppress strangeness-changing neutral currents in $K^0\bar{K}^0$ mixing to explain the small $K_1^0-K_2^0$ mass difference. Now, only two years later, the GIM mechanism was seen to fit naturally into the Weinberg-Salam model, allowing $\Delta S = 0$ neutral currents while suppressing those with $\Delta S \neq 0$. In a more recent publication Cundy et al. 1970 [26] withdrew the original result on elastic scattering by neutral current interaction. The way was open for a new search and, finally, for the discovery of neutral currents.

II.3 Structure of the neutral current

Following the discovery of a new weak force in muon-neutrino elastic scattering on electrons and in inelastic neutrino scattering on nucleons its Lorentz and isospin structure was determined from further neutrino experiments and from electron-positron annihilation experiments.

The existence of $\bar{\mu}\mu$ and $\bar{\tau}\tau$ neutral currents was deduced from the observation of a weak forward-backward charge asymmetry in the annihilation of electrons and positrons at the PETRA collider at DESY [27] in 1982. The existence of other neutral quark currents, for example, $\bar{s}s$ and $\bar{c}c$, was deduced from the analysis of the inelasticity distribution of deep inelastic neutral current neutrino scattering on nucleons [28] and from J/ψ production [29], respectively. Also the neutral current $\bar{\nu}_e\nu_e$ has been observed in neutrino experiments at CERN [30].

So far, only diagonal neutral currents have been observed that do not change the flavour of the particles involved. With three families of leptons and quarks, the standard theory [31] predicts the existence of six diagonal neutral lepton currents and six diagonal neutral quark currents.

The neutral current has a more complex helicity structure than the charged current. Experiments, for example, measurements of the inelasticity distribution of deep inelastic neutral current neutrino scattering [32, 33], have shown that coupling to both left-handed and right-handed quarks exist. This observation shows directly the existence of a unified, electroweak force. Its existence was demonstrated by the observation of interference of amplitudes with γ and Z^0

interchange, for example, in the helicity asymmetry of electron-deuteron scattering [34] and in the optical activity of Bismuth and Cesium vapour [35, 36].

The structure of the current as deduced from these experiments implies that left-handed fermions transform as doublets under a weak isospin rotation group and right-handed fermions transform as singlets. The Standard Model of the electroweak gauge theory predicted this structure of neutral currents and it successfully describes a large amount of experimental data [37, 38, 39, 40, 41] which are all consistent with universal strength of the forces g_2 and g_1 associated with the SU(2) and U(1) symmetry groups, respectively.

The fundamental quantities of the Standard Model, the coupling constants g_1 and g_2 , and the masses of the weak bosons m_W and m_Z are related to the angle Θ_W that describes the mixing of the two local symmetries by the relations

$$e = \frac{g_1 g_2}{\sqrt{g_1^2 + g_2^2}} = g_2 \sin\Theta_W, \quad \sin^2\Theta_W = 1 - \frac{m_W^2}{m_Z^2}.$$

The value of the mixing angle is not predicted by the Standard Model. Grand unified theories predict a value of $\sin^2\Theta_W = \frac{3}{8}$ at the unification mass.

The occurrence of a nonzero mixing angle defines both the structure and the strength of the neutral currents. The left-handed "up" particles of the weak isospin doublets couple with a coefficient $(\frac{1}{2} - Q \sin^2\Theta_W)$, where Q is the electric charge of the particle. The coupling coefficient of the right-handed states is $-Q \sin^2\Theta_W$. Hence, the value of $\sin^2\Theta_W$ can be deduced from all neutral current-induced processes.

II.3.1 Neutrino identity

Since the discovery of the neutral weak current, it has generally been believed that in neutrino-induced processes

$$\nu_\mu N \rightarrow \nu' X$$

$$\nu_\mu e \rightarrow \nu' e$$

the neutral lepton in the final state (ν') is identical with the incident neutrino. The identity is suggested by the assumption that the neutral neutrino current $(\bar{\nu}_\mu \nu_\mu)$ and the neutral electron $(e^+ e^-)$ and the quark currents $(\bar{u}u, \bar{d}d, \text{etc})$ couple by exchanging a neutral intermediate boson, in analogy with the CC coupling. The possibility of nonidentity has been excluded in two ways.

One source of information is the behaviour of the differential cross sections of ν and $\bar{\nu}$ induced processes in the limit $Q^2 \rightarrow 0$ for exclusive reactions or

$y = 1 - \frac{E_{\nu'}}{E_{\nu\mu}} \rightarrow 0$ for inclusive reactions. We expect

$$d\sigma(\nu) = d\sigma(\bar{\nu})$$

as $q^2, y \rightarrow 0$ if $\nu = \nu^1$. Experimental data obtained by the CDHS (WA 1) Collaboration led by J. Steinberger [42] and by the CHARM (WA 18) [43] Collaboration led by K. Winter at CERN are compatible with this equality and, hence, assuming only V, A interactions, support the concept of neutrino identity.

The other source of information is electron-neutrino scattering on electrons. Observation of interference of amplitudes from NC and CC interactions again supports the concept of neutrino identity [44].

II.3.2 Lorentz structure

Observation of an asymmetry of the scattering cross sections of left-handed and right-handed electrons on deuterons at SLAC (Stanford) in 1978 [45] demonstrated that the interaction of the $\bar{e}e$ NC is parity violating. In terms of the space-time structure of the current, because of the interference with the electromagnetic interaction this is direct evidence for vector (V) and axial vector (A) $\bar{e}e$ currents. This was confirmed by the observation that the plane of polarization of a beam of circularly polarized laser light passing through Bismuth or Cesium vapour is rotated [46].

Is the Lorentz structure of the neutrino NC interaction of the helicity-conserving vector (V, A) type or of the helicity-changing scalar, pseudoscalar or tensorial type? Elucidating this question for the CC weak interaction took nearly 25 years of experimental investigation. In neutrino-induced reactions the answer is further obscured by the so-called confusion theorem.

The cross section ratios

$$R = \frac{\sigma_{\nu}^{NC}}{\sigma_{\nu}^{CC}}, \quad \bar{R} = \frac{\sigma_{\bar{\nu}}^{NC}}{\sigma_{\bar{\nu}}^{CC}}, \quad r = \frac{\sigma_{\bar{\nu}}^{CC}}{\sigma_e^{CC}}$$

are given in the electroweak theory in terms of the mixing parameter (Weinberg angle) $\sin^2\theta_W$. On the basis of these ratios the Gargamelle experiment yielded a first measurement of $\sin^2\theta_W$ [47]. The neutrino beams of higher energies that became available at CERN with the 450 GeV SPS machine made more precise measurements possible. The separation of NC and CC reactions was much cleaner because of the higher muon energy and greater muon penetration. Electronic detection techniques gained several advantages over the bubble chamber technique. Among them is fast timing to eliminate the associated neutron background that plagued the Gargamelle experiment, the large detector mass and dimensions compared to the interaction length of hadrons, and the calorimetric measurement of hadron energy with high resolution ($\Delta E/E \sim 50\%/\sqrt{E/\text{GeV}}$) owing to the fine segmentation of the target plates.

The results, given in Table 1, show good agreement of results obtained by the CDHS and CHARM Collaborations at CERN.

Table 1. Values of cross section ratios R , $\bar{R}$, and r and values of $\sin^2\Theta_W$ (radiative corrected for $m_t = 45$ GeV and $m_H = 100$ GeV) derived from them

Experiment	R	$\bar{R}$	r	$\sin^2\Theta_W$
CDHS [48]	0.3072 ± 0.0032	0.382 ± 0.016	0.494 ± 0.013	0.225 ± 0.005
CHARM [49]	0.3093 ± 0.0031	0.390 ± 0.013	0.486 ± 0.013	0.236 ± 0.005

Note: $m_c = 1.5$ GeV The common theoretical uncertainty is $\Delta\sin^2\Theta_W = \pm 0.003$.

^a Event-length method.

^b Event-by-event method.

The combined value with radiative corrections for $m_t = m_H = 100$ GeV is

$$\sin^2\Theta_W = 0.230 \pm 0.004(\text{exp}) \pm 0.003(\text{theor}).$$

This result defines both the structure and the strength of the neutral currents and predicts the masses of the intermediate bosons

$$m_{Z^0}(\text{predicted}) = 91.6 \pm 0.9 \text{ GeV}$$

$$m_W(\text{predicted}) = 80.2 \pm 1.1 \text{ GeV}.$$

The ratio of the NC coupling to right-handed and left-handed quarks can also be derived from these measurements of cross section ratios. However, it is evident that one cannot demonstrate the handedness of the fermions participating in the NC interaction by measurements of scalar quantities. Using the approach by Llewellyn-Smith [50] relating the differential cross sections of neutrino and antineutrino scattering on isoscalar targets (equal numbers of neutrons and protons) by the NC and CC interaction

$$\begin{aligned} \frac{d\sigma_{NC}^{\nu}}{dy} &= g_R^2 \frac{d\sigma_{CC}^{\nu}}{dy} + g_R^2 \frac{d\sigma_{CC}^{\bar{\nu}}}{dy} \\ \frac{d\sigma_{NC}^{\bar{\nu}}}{dy} &= g_R^2 \frac{d\sigma_{CC}^{\nu}}{dy} + g_L^2 \frac{d\sigma_{CC}^{\bar{\nu}}}{dy} \end{aligned}$$

the NC coupling to left-handed quarks (g_L^2) and to right-handed quarks (g_R^2) has been determined by the CHARM Collaboration [51].

In neutral current neutrino reactions the outgoing neutrino (ν') cannot be observed and, hence, the inelasticity $y = E_h / (E_h + E_{\nu'})$ cannot be determined on an event-by-event basis. One must resort to a sign and momentum selected parent beam, a so-called narrow band beam. A high quality beam of this type had been built for the first time at the CERN SPS. Owing to the dominant two-body decays $\pi \rightarrow \mu \nu_\mu$ and $K \rightarrow \mu \nu_\mu$ that produce the neutrinos, a measurement of the neutrino direction implies a determination of the neutrino energy, apart from the π, K ambiguity. The neutrino direction can be inferred from the distance of the neutrino interaction point from the beam axis. The differential cross sections of CC and NC deep inelastic scattering, thus determined, are shown in figure 2.4; from a fit to the Llewellyn-Smith relations the CHARM Collaboration determined [51]

$$g_L^2 = 0.287 \pm 0.008$$

$$g_R^2 = 0.042 \pm 0.010$$

in good agreement with the values determined from $\sin^2\Theta_W = 0.230$ in the context of the electroweak theory [52]. The NC coupling of right-handed quarks (g_R^2) is shown to be nonzero at the four σ level.

The value of the electroweak mixing parameter $\sin^2\Theta_W$ determined from deep inelastic neutrino scattering affected also the discussions about Grand Unification Theories (GUT) into which the electroweak gauge groups $SU(2) \times U(1)$ would be embedded. The minimal $SU(5)$ group proposed as a candidate for GUT by Georgi and Glashow predicted a value which is 3σ below the experimental result. Together with the absence of proton decays at the predicted rate this led to abandoning $SU(5)$ as a GUT candidate and to new interest in other theories like supersymmetry which predicted additional mass states and a larger value of $\sin^2\Theta_W$.

Figure 2.4 Differential cross sections of $\nu_\mu N$ and $\bar{\nu}_\mu N$ deep inelastic scattering by neutral current and charged current interaction (CHARM Collaboration) [51].

II.3.3 Neutrino electron scattering

In the standard $SU(2) \times U(1)$ electroweak theory, all left-handed fermions are assumed to transform as doublets with respect to weak $SU(2)$, and right-handed fermions as singlets. Neutral current data can directly measure the $SU(2) \times U(1)$ properties of the fermions. The cleanest approach in principle to this goal would be by measuring the cross section of $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering as this process proceeds by neutral current interaction alone and involves only leptons. However, the cross sections are small, some 10^{-42} . $E_\nu[\text{cm}^2/\text{GeV}]$, smaller than those of hadronic processes by the ratio m_e/m_p because of the smaller c.m. energies, and, consequently, the event rates are low and the background large.

'tHooft, then a young physicist at the University of Utrecht has derived the expressions for the differential cross section in the framework of the $SU(2) \times U(1)$ gauge theory [52] :

$$\begin{aligned}\sigma_{\nu_\mu e} &= \frac{\sigma_0}{2} E_\nu \left[g_L^2 + \frac{1}{3} g_R^2 \right] \\ \sigma_{\bar{\nu}_\mu e} &= \frac{\sigma_0}{2} E_\nu \left[\frac{1}{3} g_L^2 + g_R^2 \right]\end{aligned}$$

where $y = E_e/E_\nu$, $g_L = g_V^e + g_A^e$, $g_R = g_V^e - g_A^e$ and the nominal cross section slope is

$$\sigma_0 = \rho^2 \frac{G_F^2 m_e}{\pi} = 8.6 \cdot 10^{-42} \text{ cm}^2/\text{GeV}$$

assuming $\rho = G_{NC}/G_F = 1$.

A fourfold ambiguity for exchanging g_V^e and g_A^e is remaining if these cross sections are measured. Two solutions can be eliminated by $\bar{\nu}_e e$ or $\nu_e e$ scattering experiments, a third solution by measurements of the forward-backward asymmetry in the reaction $e^+e^- \rightarrow \mu^+\mu^-$ under the assumption that weak neutral current processes are dominated by the exchange of a single Z^0 .

A first attempt to measure the cross sections was made by an Aachen-Padova Collaboration led by H. Faissner and M. Baldo-Ceolin [53] at the CERN PS. An array of aluminium plate optical spark chambers with a fiducial weight of 18 tons was operated in an unbiased way by pulsing the spark chamber high voltage on every accelerator pulse. In total 12 $\nu_\mu e$ candidates and 10 $\bar{\nu}_\mu e$ candidates with a signal to background ratio of about 1 : 2 were observed. Following this early pioneering attempt the CHARM (CERN-Hamburg-Amsterdam-Rome-Moscow) Collaboration made measurements [54] at the CERN SPS using marble target plates of 70 tons of fiducial mass and proportional tube chambers and scintillator hodoscopes of fine segmentation. In total 200 $\nu_\mu e$ and $\bar{\nu}_\mu e$ event candidates were observed, after subtraction of a background of similar magnitude. Combining them with data from PETRA (DESY, Hamburg) [55] and with $\bar{\nu}_e e$ data from a nuclear reactor [56] this result resolved for the first time the fourfold ambiguity and determined $g_A^e = -0.57 \pm 0.04(\text{stat}) \pm 0.06(\text{syst})$ in agreement with the $SU(2)$ doublet symmetry scheme.

The original guess was thus confirmed experimentally. As the Standard Model does not distinguish between families of fermions it was natural to take the same doublet assignment of muons and taus as well. These were confirmed by measurements of annihilation processes at PETRA [55] and LEP [58].

More recently, another step in the precision of measuring the total and the differential cross sections of $\nu_\mu e$ and $\bar{\nu}_\mu e$ scattering has been achieved by the CHARM-II Collaboration at CERN led by K. Winter. Using a new detector of low Z target material (glass) with 500 tons fiducial mass and finer segmentation and detector elements of smaller width they improved the statistics to 4500 $\nu_\mu e$ and $\bar{\nu}_\mu e$ candidates. From the ratio of the cross sections they determined $\sin^2\Theta_W$ and from the absolute differential cross sections the values of the coupling constants g_A^e and g_V^e [59]. The result is compared in figure 2.5 with those on the crossed diagram $e^+e^- \rightarrow e^+e^-$ which has been studied at LEP [58]. The agreement is remarkable, keeping in mind the difference in energy scale, a c.m. energy of ~ 100 MeV in $\nu_\mu e$ scattering and of 90 GeV at LEP. Radiative corrections due to the running of the fine structure constant α and the neutrino charge radius tend to cancel each other when calculated in the electroweak theory. Compared to the divergent electromagnetic corrections in the Fermi theory, the progress is very significant.

Figure 2.5 Electroweak electron couplings determined from e^+e^- annihilation at the Z^0 [58] and from neutrino-electron scattering [59].

II.3.4 Isospin Structure of the neutral quark current

Measurements of inclusive neutral-current neutrino scattering on isoscalar targets determine two combinations of the chiral coupling constants of the u and the d quarks, $u_L^2 + d_L^2$ and $u_R^2 + d_R^2$. Measurements of inclusive neutrino scattering on protons and neutrons were required to determine the coupling of the u and the d quark separately.

These measurements remained the exclusive domain of the Big European Bubble Chamber (BEBC) built at CERN by a Collaboration between CERN, France and Germany which had been set-up and operated through the initiative and under the guidance of W. Jentschke, F. Perrin and V.F. Weisskopf. Originally built for the 28 GeV Proton Synchrotron this chamber had been adapted to the needs of neutrino physics at the 450 GeV SPS by equipping it with new electronic devices, an external muon identifier, a veto plane and an internal picket fence (see figure 2.6). The chamber was filled, successively, with hydrogen, deuterium and with a mixture of neon and hydrogen. Inside this heavy mixture a track sensitive target, filled with hydrogen or deuterium had been installed for some time, with the aim of using the heavy liquid as a detector for γ -rays carrying a large fraction of the hadron energy in inclusive deep inelastic neutrino reactions.

Figure 2.6 The big European bubble chamber (BEBC) at CERN with external muon identifier (EMI), veto plane and internal picket fence (IPF).

Simultaneous measurements of four ratios of NC and CC cross sections, of neutrinos and antineutrinos on protons and neutrons have been performed by one Collaboration [60] using BEBC filled with deuterium. The target particle could either be a proton or a neutron. The cases were distinguished by the number of detected tracks; events with odd (even) numbers of tracks correspond to interactions with protons (neutrons). Two effects, due to Fermi motion and to rescattering are not described by this simple scheme. A correction is applied for them.

Another Collaboration [61] used BEBC with a track sensitive liquid hydrogen target and measured the ratio of π^+/π^- in the four NC and CC reactions on protons induced by neutrinos and antineutrinos. The ratio π^+/π^- is sensitive to the quark composition produced in the primary neutrino-quark interaction and, although somewhat model dependent, it gives better precision than the cross section ratios.

The results are summarized in Table 2, together with the Standard Model predictions for $\sin^2\Theta_W = 0.230$. The relative signs of the chiral coupling constants cannot be determined from inclusive experiments. They have been determined from exclusive channels (elastic NC reactions, $\nu p \rightarrow \nu p$ and $\bar{\nu} p \rightarrow \bar{\nu} p$, $\nu_\mu A \rightarrow \nu_\mu \pi^0 A$, $\bar{\nu}_e d \rightarrow \bar{\nu}_e pn$). The overall sign is determined from interference between Z^0 and photon exchange in electron-deuterium scattering and atomic parity violation. Except for d_R that is determined with large uncertainty the agreement with the Standard Model is excellent.

In later years and in particular with the high precision results obtained from e^+e^- annihilations at LEP the Standard Model became a reference from which no deviation was seen. The situation was in many ways similar to that of tests of QED in the 1960's. Although not a complete theory, the Standard Model will have to be part of that theory.

Table 2. Values of neutral current quark couplings constants determined from neutrino experiments

Coupling constant	Value	Standard Model prediction
u_L	0.339 ± 0.017	0.345
d_R	-0.429 ± 0.014	-0.427
u_R	-0.172 ± 0.014	-0.152
d_R	-0.011 ± 0.081 $- 0.057$	-0.076

Note: The Standard Model prediction is given from $\sin^2\Theta_W = 0.230$.
Source: [62; 63].

II.4 Structure of the weak leptonic charged current

The main subject of experimental neutrino physics, following the seminal paper by T.D. Lee and C.N. Yang in 1960 [64], had been a search for the bosons $W^\pm$ which are mediating the weak charged current interaction. The rise of the cross section of point-like particles such as neutrino-electron scattering would, in the four-fermion-point-interaction picture, reach, at a center of mass energy of $\sqrt{s} = \sqrt{\pi/G} \sim 320$ GeV the s-wave unitarity limit of $\sigma = G/\pi \sim 10^{-33} \text{cm}^2$. Thus, at small distances, corresponding to these energies, Lee and Yang argued, the weak interaction must be modified in order to avoid a violation of unitarity. Such a modification could be obtained by the propagator effect of a non-locality introduced by a finite mass intermediate boson.

Lee and Yang had calculated the cross section for neutrino production of the W in the Coulomb field of a heavy nucleus of charge Z

$$\nu_{\mu} Z \rightarrow \mu^{-} W^{+} Z .$$

The cross section has a strong dependence on the W mass. "If experimentally no $W^{\pm}$ is found," they wrote, "it would be possible to set a lower limit on the value of m_W " [64].

Following the discovery of a second neutrino associated with the muon, the muon neutrino at Brookhaven in 1962 by L. Lederman, M. Schwarz, J. Steinberger and collaborators [65], a new neutrino program was started at CERN in 1963. Using a spark chamber set-up and a heavy liquid bubble chamber exposed to the new high quality neutrino beam (see figure 2.7) the discovery of the muon neutrino was confirmed with high statistics [66]. Also some events due to electron-neutrino interactions were observed, at the rate expected from $K^{+} \rightarrow \pi^{0} e^{+} \nu_e$ decays. Another important result was obtained by focussing negative pions and kaons by the horn, thus producing a beam of antimuon neutrinos. Their interactions were observed to produce exclusively positive muons [67] in agreement with the notion of lepton number conservation. Left-handed muon neutrinos produce negative muons, whereas right-handed antimuon neutrinos produce positive muons.

Figure 2.7 The horn focussed neutrino beam at CERN.

The energy of the PS neutrino beam is peaked in the region of a few GeV and was, thus, suitable to search for the production of the W^{+} with a mass below 2 GeV. The leptonic decay modes of the W^{+}

$$\begin{aligned} W^{+} &\rightarrow \mu^{+} \nu_{\mu} \\ W^{+} &\rightarrow e^{+} \nu_e \end{aligned}$$

were searched for as they provide the cleanest signature. A few candidates of events with the topology $\mu^{-} e^{+}$ and $\mu^{-} \mu^{+}$ were indeed observed in the spark chamber set up [68]. One event is shown in figure 2.8. In a moment of uncertainty these events were interpreted as candidates of W decays. However, after careful

calibration a lower limit of $m_W > 1.8 \text{ GeV}$ was quoted. The bubble chamber [69] gave a model independent lower limit by integrating over all decay modes of $m_W > 1.5 \text{ GeV}$.

Later, Helmut Faissner, who was one of the leaders of the spark chamber detector, said that the events, which had been tentatively attributed to W decays, may have been the first candidates of charm particle decays.

Figure 2.8 An example of a (μe) event [68] observed in the 1964 neutrino experiment at CERN.

The search of $W^\pm$ remained at the top of the list of physics motivations for the construction of Gargamelle at CERN and for the construction of Experiment 1A at the Fermi National Accelerator Laboratory in the U.S.A. Following the discovery of neutral current weak interactions in 1973, the theory of electroweak interactions of Glashow, Salam and Weinberg made, for the first time, a prediction of $m_W \sim 80 \text{ GeV}$. This large value was out of the reach of the neutrino beams at the CERN SPS and the FNAL 400 GeV accelerators and the subject was dropped. The CDHSW Collaboration led by Jack Steinberger made an attempt to search for the W propagator effect in the cross section dependence on q^2 [70]. But the interpretation remained ambiguous because of similar effects introduced by scaling violation (see II.5).

From studies of beta-decay processes in nuclei in the MeV domain the charged current weak interaction had been found to be of the V-A type. With the advances in particle accelerators it became possible to test the structure of weak charged currents at higher energies and higher momentum transfers in the GeV domain. The improvement of neutrino beams at the CERN SPS and the existence of the two large detectors, that of the CDHS Collaboration and that of the CHARM Collaboration, opened the possibility to measure the helicity of the positive muons produced in the reaction

$$\bar{\nu}_\mu N \rightarrow \mu^+ X \quad .$$

The positive helicity of the antineutrino would be preserved if the interaction was of V and A type, whereas interactions of the S(scalar), P(pseudoscalar) and T(tensor)-type would flip the helicity. Such an experiment therefore constitutes a very direct test.

The experimental set-up consists of two parts [71], the target and the polarimeter. The neutrino detector of CDHS served as an active target. The CHARM detector was used as a muon polarimeter. Muons stopped in the (marble) plates, chosen to minimize depolarization effects and the muon spin precessed in a magnetic field with a period of $1.3\mu\text{s}$.

The time dependent forward-backward asymmetry of high energy positrons from muon decay was measured (see figure 2.9) and its phase and magnitude was found to correspond to initially fully right-handed muons. An upper limit of $\sigma_{S,P}/\sigma_{TOT} < 7\%$ (95% C.L.) was given. It can be concluded that the weak leptonic charged current remains dominantly composed of V and A currents at momentum transfers of several GeV^2 .

The reaction

$$\nu_\mu e^- \rightarrow \mu^- \nu_e$$

is a purely leptonic process mediated by charged currents. A measurement of its cross section can complement the precise measurements of muon decay, $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$, the inverse reaction. Assuming left-handed neutrinos the measurements [72] found good agreement with V-A coupling, whereas right-handed neutrinos or S, P coupling were excluded at the 6 standard deviation level.

Figure 2.9 Observed time dependence of the oscillating forward-backward asymmetry of positrons from polarized muons [71].

II.5 The quark structure of matter

In the first publication in 1964 of neutrino results obtained in the CERN heavy liquid bubble chamber [73], a "marked increase of the inelastic cross section with neutrino energy" was reported (see figure 2.10). This phenomenon was also discussed by Perkins [74] and by Bell, Løvseth and Veltman at the 1963 Sienna Conference [75]. Perkins reported, "The total inelastic neutrino cross section rises rapidly with neutrino energy, perhaps as E_ν^2 , but the energy spectrum of the flux enters and this is still quite uncertain." He is also asking for possible explanations for this rise and gives two: (1) the form factor of the scattering may be associated with a hard nucleon core, (2) increase of the inelasticity. Bell et al. remarked [75]: "this rise in the inelastic cross section is one of the most striking features of the experiment."

Hence, both experimentalists and theorists were alerted by this very unusual phenomenon. Never before had a total cross section been observed to rise linearly with energy. If this was due to the opening up of new channels with higher mass one would expect the cross section to level off at some higher energy. Perkins with the proposal of a hard core had come very close to the later interpretation. Bell, in a seminar on neutrino physics [76] in 1963 at CERN, had calculated that the cross section of neutrino electron elastic scattering was expected to rise linearly with E_ν owing to the point-like nature of the leptons and of the 4-fermion-interaction involved, but in October of the same year, at Sienna, he did not make the connection with the rising total cross section.

Figure 2.10 Cross section of inelastic events observed in the CERN heavy liquid bubble chamber in 1964 [69].

Later, in 1969, following the discovery of very similar phenomena in deep inelastic electron scattering at the 2-mile linear accelerator SLAC (Stanford, U.S.A.), Perkins [77] reported at a Topical Conference on Weak Interactions organised by J. Bell at CERN, "another, and quite different way to arrive at point-like cross sections is to postulate point-like constituents in the nucleon. These constituents can be imagined as "bare" quarks if anyone can imagine such objects." He continued by saying, "If one sums over all elastic and inelastic channels the total

cross section will be given by the elementary lepton-quark elastic cross section, i.e. $d\sigma/dq^2 = \text{constant}$. This model is almost unbelievably crude, and, as K. Gottfried has remarked [78], no well educated person should be expected to accept it. Yet, it at least has the virtue of making rather definite predictions." Again, in 1969, at the Lund Conference, J. Steinberger [79] referred to the rise with neutrino energy of the total neutrino cross section and compared it to the elastic cross section. "The levelling off of the elastic cross section already below 1 GeV, consistent with form factors of the same general behaviour as the electromagnetic form factors, while the total cross section is still seeming to increase linearly up to neutrino energies of ~ 12 GeV, consistent with a point interaction (see figure 2.11) made the greatest impression on me."

Figure 2.11 Energy dependence of elastic and of total neutrino cross section [79].

Neutrinos are ideal projectiles for investigating this structure, owing to the large mass of the intermediate boson and the corresponding nearly point-like interaction, and also because neutrinos are scattered differently by quarks and anti-quarks owing to the V-A nature of the weak currents. Scattering of neutrinos on quarks and on antiquarks can therefore be distinguished whereas in electron or muon scattering this is not possible. The quark model makes definite predictions for neutrino-nucleon scattering which were beautifully confirmed

experimentally. Although the merit of the discovery of the quark structure and the Nobel prize for it went to Friedman, Kendall and Taylor who were leading the experiment at SLAC, the role of CERN in confirming the predictions of the quark model was very important.

The proton contains three so-called 'valence' quarks, two up-quarks and one down-quark. In addition it contains a 'sea' of virtual quark-antiquark pairs. Sea quarks and antiquarks have necessarily identical distributions as a function of the Feynman scaling variable x which has a physical interpretation as the fraction of the nucleon momentum or mass carried by the quark. For the neutron, u and d quarks change their roles whereas the sea quarks are the same.

In the simple quark model, describing the scattering cross section of neutrinos and antineutrinos on quarks, the absence of a finite size of quarks translates into an absence of a dependence on q^2 , the momentum transfer from the neutrino to the muon, in the inclusive processes

$$\nu_{\mu} N \rightarrow \mu^{-} + \text{hadrons}$$

$$\bar{\nu}_{\mu} N \rightarrow \mu^{+} + \text{hadrons} .$$

This property, also called 'scaling' by Feynman and Björken [80], is experimentally evident everywhere, e.g. in the linear rise of the total cross sections with neutrino energy [81], in the uniformity of the average inelasticity y with respect to the neutrino energy [81]. These striking scaling properties are a consequence of the point-like interaction of the quark. In these experiments, one measures the momentum and angle of the muon and the kinetic energy of the hadrons using sampling calorimeters. The invariants describing the kinematics of the inclusive reactions can be calculated in terms of these measured quantities :

$$E_{\nu} = E_{\text{hadron}} + E_{\mu}$$

$$Q^2 = 4E_{\mu}E_{\nu}\sin^2\theta_{\mu}/2$$

$$X = Q^2/2m_p E_{\text{hadron}}$$

$$y = E_{\text{hadron}}/E_{\nu}$$

The y dependence of the cross sections is directly reflecting the helicity of the neutrino and of the spin 1/2 quark which interact. A claim for a y -anomaly (so-called high y anomaly) by a Harvard-Pennsylvania-Wisconsin-Fermilab group was reported [82] in 1976 for antineutrino scattering at high energies. The apparent flattening of the antineutrino y distributions along with a rapid rise of the ratio of antineutrinos and neutrino total cross sections at high energy reported by the same group [83] led to considerable conjecture about possible new phenomena at high energies. However, the CERN results of the CDHS collaboration [81]

and results obtained by a Caltech-Fermilab experiment [84] contradicted these claims. The observed energy independence of the average fraction of the neutrino energy transferred to the hadronic final state, y and the slow variation of the ratio of $R = \sigma_{\bar{\nu}}/\sigma_{\nu}$ did not support these claims.

However, there appeared another disagreement, in the values of the linear slopes of the rise with neutrino energy of the total cross sections. The Caltech-Fermilab experiment [84] reported values which are 15% higher than those measured by the CDHS Collaboration at CERN. This conflict was resolved by later experiments at CERN [85] using new monitoring equipment for determining the neutrino flux; they confirmed the earlier Caltech-Fermilab results. The disagreement was traced back to errors in the secondary hadron beam intensity measurements at CERN [86].

Combining data from neutrino and anti-neutrino scattering one can determine structure functions which are related to the quark structure of the nucleon. $F_2(x, Q^2)$ is reflecting the total quark and anti-quark distribution, $q(x)+\bar{q}(x)$; $xF_3(x, Q^2)$ is related to valence quark distribution, $q(x)-\bar{q}(x)$. Comparing F_2 as determined from deep inelastic electron or muon scattering ($F_2^{\ell}(x)$) and from neutrino scattering ($F_2^{\nu}(x)$) from isoscalar nuclei we expect them to be proportional to the same quark distribution, $q(x)+\bar{q}(x)$. They are therefore related by the average of the squared electric charges of the down-and up-quarks,

$$\frac{F_2^{\ell}(x)}{F_2^{\nu}(x)} = \frac{1}{2} \left[\left(-\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 \right] = \frac{5}{18} .$$

The agreement in shape and in magnitude of the measurements of $F_2^e(x)$ at SLAC [87] and of $F_2^{\nu}(x)$ at CERN [88] supported the quark picture and demonstrated that quarks have fractional electric charges. This remarkable confirmation of the quark model of the nucleon was first reported at the 1972 Rochester Conference at Batavia and Chicago. Following the demonstration at SLAC that partons have spin 1/2, the remaining most decisive question was: What is their electric charge? Theoretical work of Gourdin [89], Nachtmann [90], Llewellyn-Smith [91] and Feynman [92] had led to the prediction of the ratio of neutrino and antineutrino total cross sections and of the structure functions F_2 . The electric charge of the quarks, if there were any in the nucleon, could be read off the deep inelastic electron and neutrino scattering. Experimental results obtained by the Gargamelle Collaboration could finally be compared to the electron data from SLAC. But the important conclusion that the comparison indeed agreed with fractionally charged quarks was only given in the discussion [93] following the report on the neutrino experiment [93] and immediately acclaimed by Feynman. Perkins reported the result in his rapporteur talk at this conference [94].

The number of valence quarks can be determined from an integral of the structure function xF_3 ; a value of

$$\int xF_3(x) dx/x = 3$$

is expected in the simple quark model. Although the experimental demonstration is not without problems all experiments [95] give a value near 3, actually below 3, with typical uncertainties of $\sim 10\%$.

The neutrino experiments are unique for measuring, independently, the quark and antiquark distributions in the nucleon. Together with the charged-lepton inclusive experiments they leave no doubt about the validity of the quark picture of nucleon structure.

If quarks were the only nucleon constituents one would expect the integral of F_2 to be equal 1,

$$\int F_2(x)dx = \int x[q(x) + \bar{q}(x)]dx = 1.$$

Experiments [96] found a value of $\int F_2(x)dx \sim 0.50 \pm 0.02$, indicating that about one-half of the nucleon momentum is carried by other constituents which do not interact with neutrinos. The gluons that are binding the quarks are expected to carry the missing half of the nucleon momentum. This point of view had first been taken by Llewellyn-Smith [97]. But the question why quarks are confined and why they behave like bosons remained obscure [92] at that time.

II.6 Scaling violations and QCD

Once the dominant scaling property of inclusive lepton-nucleon scattering had been uncovered some deviations from the predictions of the simple quark model were observed and called 'scaling violations'. Such violations of scaling, due to the strong interactions between quarks, manifest themselves through the fact that the structure functions depend not only on x but also on q^2 . These violations turn out experimentally to be weak, especially at large q^2 , as beautifully explained in Quantum Chromodynamics (QCD), the theory of the gluon-quark interaction by the colour charge, through the property of asymptotic freedom. QCD predicts logarithmic deviations from scaling and these effects should appear in high energy neutrino data and manifest themselves as a 'shrinking' of the structure functions towards smaller x as q^2 increases. This was indeed observed experimentally, as can be seen from figure 2.12. Scaling is only approximately true for the structure functions. Measurements of $F_2(x)$ in three different energy domains exhibit shrinking (fig. 2.12), as expected in the QCD theory. In that theory the 'shrinking' is the consequence of the emission of gluons in the scattering process. The rate of their emission can be calculated and the q^2 evolution of the structure function can thus be predicted and compared with the measurements. Relations between different moments of the structure functions gave first evidence for logarithmic scaling violations. The bubble chamber analysis, combining data from BEBC and Gargamelle [98] was spanning the widest q^2 range, and found agreement with the predictions of QCD (see figure 2.13). The data from the electronic experiment of the CDHS Collaboration [99] covered only the domain of high q^2 values and lend further support to this confirmation of QCD because of its high statistics.

Figure 2.12 Scaling violations. Measurements of $F_2(x)$ in three different energy domains show shrinking, as expected in QCD [17].

Figure 2.13 Relations between moments of the structure function xF_3 are well described by a power law as predicted by QCD [98, 99].

Let us pause here to examine to what extent these results may be affected by experimental uncertainties. It is important to note that data at large q^2 and $x < 0.1$ were not available because of the energy limitation of the neutrino beams; the lower moments could therefore not be evaluated. The higher moments are strongly dependent on data with $x > 0.5$ and are therefore subject to experimental resolution effects which require important corrections. Other effects, such as Fermi motion of the nucleons in the target nucleus and radiative corrections, are also large. Since, however, the main concern is the q^2 dependence of the structure functions and of their moments, these effects are negligible in comparison with the other uncertainties. In summary, there was consistency with the QCD predictions, but the quality of the test did not yet give compelling evidence for spin 1 gluons.

In the case of xF_3 , the valence quark distribution, the theoretical predictions have only one free parameter, the QCD parameter Λ in the q^2 evolution ('running') of the strong gluon-quark coupling constant (for 4 flavours)

$$\frac{\alpha_s}{\pi} = \frac{12}{25 \ln(q^2/\Lambda^2)}$$

In the case of $F_2(x)$ the q^2 evolution is coupled to the gluon distribution $G(x)$,

q^2). The experimental results on the q^2 evolution of F_2 and xF_3 (from charged lepton and neutrino scattering) can be adequately described by the theory (see figure 2.14) with a value of $\Lambda_{\overline{MS}} \sim 260$ MeV, corresponding to $\alpha_s(M_Z^2) \cong 0.113$.

II.7 New weak currents and the GIM mechanism

Neutrinos offer a unique way of producing particles with new quantum numbers by changing the nature of the quark with which they interact. Produced singly, not in pairs, the new quark cannot disappear or annihilate in a final state interaction. This was realized when a new class of events was discovered in the HPWF experiment at Fermilab [100] in 1975, consisting of two muons of opposite charge and a hadron shower. Rubbia showed that these events were due to the decay of a new particle produced at the hadron vertex. Was this naked charm? Hidden charm had been discovered by Richter and Ting in 1974 in the form of the J/ψ charmonium. The observation at Fermilab was soon studied in detail in the CDHS experiment at CERN [101]. These di-muon events occur with $\sim 1/100$ of the rate of all single-muon events. Their study confirmed the weak isospin doublet structure of quarks as proposed by Glashow, Iliopoulos and Maiani (GIM) [102] which is fundamental to the electroweak theory.

Figure 2.14 q^2 evolution (a) of $F_2(x)$ from charged lepton [86] and (b) of $xF_3(x)$ from neutrino scattering [85] as compared with QCD.

In the GIM model, the charm-producing reactions are due to new quark flavour-changing currents, in analogy to the mixing of s and d quarks introduced by Cabibbo,

Cross Section

(1) $\nu d \rightarrow \mu^- c$	$x d(x) \sin^2 \theta_c$
(2) $\nu s \rightarrow \mu^- c$	$x s(x) \cos^2 \theta_c$
(3) $\bar{\nu} \bar{d} \rightarrow \mu^+ \bar{c}$	$x \bar{d}(x) \sin^2 \theta_c$
(4) $\bar{\nu} \bar{s} \rightarrow \mu^+ \bar{c}$	$x \bar{s}(x) \cos^2 \theta_c$

with the subsequent decays $c \rightarrow \mu^+ \nu_s$ and $\bar{c} \rightarrow \mu^- \bar{\nu}_s$. The attribution of dimuon events to charm decays is experimentally supported by the following facts :

- (a) opposite -sign muon pairs are produced, but no like-sign muon pairs;
- (b) the extra muon has less energy than the leading one;
- (c) the extra muon is correlated to the hadron shower.

The cross sections are proportional to $\sin^2 \theta_c$ for d and $\bar{d}$ quarks and to $\cos^2 \theta_c$ for s and $\bar{s}$ quarks. The Cabibbo angle was known, with $\cos^2 \theta_c$ close to one and $\sin^2 \theta_c = 0.05$, very small. Reactions (1) and (2), or (3) and (4) are not experimentally distinguishable because the target nucleon contains both d and s quarks. In the antineutrino case reaction (4) dominates (3) because of the smallness of $\sin^2 \theta_c$. The x distribution for antineutrino dimuon events therefore measures the amount and the distribution of the strange sea quarks (see figure 2.15(a)). The two contributions to the neutrino dimuon events are roughly equal. Using the shape of $\bar{s}(x)$ determined from antineutrino dimuon events and of $d(x)$ from normal charged current events one can fit the observed shape (see figure 2.15(b)). The ratio of the two contributions is a measure of θ_c . The Cabibbo angle obtained in this way agrees, within errors, to θ_c measured in strange particle decays, as proposed in the GIM model.

Figure 2.15 The x-distributions of opposite-sign dimuon events : source [101], (a) for antineutrinos (b) for neutrinos.

Further support for the GIM model was provided by the y distributions. They were found to be flat, reflecting equal helicities of the neutrino and the struck quark. This is particularly striking in the antineutrino case, where the single muon events have a falling, $(1-y)^2$, distribution, because of opposite neutrino and quark helicities.

A spectacular event with the formation of a D^* charmed vector meson which decays in a D meson and a pion, observed in BEBC is reproduced in figure 2.16. The D meson then decays into a K meson and pions, the K meson collides with

a proton and produces a Σ hyperon. Worth a special mention is the first determination of the lifetime of charmed particles in an experiment [103] combining BEBC and the emulsion technique. The measured lifetime, roughly $5 \cdot 10^{-13}$ s, agreed with theoretical expectations.

Figure 2.16 Production and decay of a charmed D^* meson in a neutrino proton interaction in BEBC.

III. Discovery of the bosons of the weak interactions W and Z

First experimental evidence favoring a unified description of the weak and electromagnetic interactions had been obtained in 1973 with the discovery of neutral current interactions of neutrinos at CERN [15, 16]. Within the framework of the Standard Model, this experiment gave a first estimate of the electroweak mixing parameter $\sin^2\theta_W$ which led to the first prediction of a new mass scale, that of the W boson ranging from 60-80 GeV/c^2 and that of the Z boson ranging from 75-92 GeV/c^2 . This mass range was not accessible for any of the accelerators in operation at that time. An e^+e^- collider is the ideal machine to produce the Z^0 boson in e^+e^- annihilations and to study its properties, and the W boson in pairs ($e^+e^- \rightarrow W^+W^-$) at total energies in excess of $2m_W c^2$. A large e^+e^- collider has come into operation at CERN in 1989 and has contributed to the study of the reaction $e^+e^- \rightarrow Z^0$ with large statistics. The threshold of W pair production is expected to be reached in 1995.

While colliders of this type were already being considered and designed in the 1970's, a quick and relatively inexpensive way of producing W and Z bosons (if they existed) was proposed by Rubbia, Cline and McIntyre [104]. Their proposal was to transform the existing 450 GeV CERN Superproton synchrotron (SPS) into a proton-antiproton collider. In this scheme, a proton and an antiproton

beam, each of energy E , circulate on identical orbits in the same ring of magnets in opposite directions, providing head-on collisions at a total centre-of-mass energy of $2E$, a value much larger than that achieved by colliding one beam with a proton at rest. The proposal met initially with scepticism; machine builders, in particular, were hesitant to have their brand-new SPS transformed into a test ground for the $p\bar{p}$ collider. Carlo Rubbia stood alone against nearly everyone else in trusting that the collider will work and succeeded, by-and-by, to convince them.

This scheme was adopted at CERN in 1978 under the leadership of Carlo Rubbia. The directors-general of CERN at that time, John Adams and Leon van Hove, put the full technological power of CERN behind this ambitious project. The main difficulty was to obtain a sufficiently high $p\bar{p}$ collision rate for producing W 's and Z 's by fusing a quark from a proton and an antiquark from an antiproton together. To achieve the required luminosity for producing the intermediate bosons at an observable rate, antiproton beams of high particle density had to be obtained. Since the cross section for producing the W and Z particles at centre-of-mass collision energies of about 500 GeV was calculated to be of the order of a few nanobarns (1 nanobarn = 10^{-33}cm^2), a luminosity in excess of $10^{28}\text{cm}^{-2}\text{s}^{-1}$ was necessary to produce a few intermediate bosons per day of collider operation.

Antiprotons are produced in proton-nucleus collisions at a low rate, typically 10^{-6} – 10^{-5} antiprotons per incident proton. They have therefore to be accumulated in a special storage ring over several hours. However, although sufficient in number, the accumulated antiproton beam has a very small phase-space density resulting from the typical "temperature" of ~ 300 MeV for particles produced in proton-nucleus collisions. It is, therefore, necessary to apply a "cooling" technique to increase the $\bar{p}$ density to values close to those of the proton beam.

The technique of stochastic cooling, invented by Simon van der Meer in 1972 [105] was adopted. It is making use of the fluctuations of the average beam position in phase space that occur because the beam contains a finite, though large number of particles. These fluctuations are detected by means of pick-up electrodes around the antiproton accumulator ring. Correction signals are then generated and applied, over a period of time of several minutes, at other points of the ring to either accelerate or decelerate the beam according to the prevailing average beam position detected. In this way $10^{11}\bar{p}$'s per day have been accumulated and cooled, accelerated together with protons to 26 GeV in the CERN Proton Synchrotron (PS), transferred to the SPS and accelerated to 270 GeV and after 1984 to 315 GeV (see figure 3.1).

First $p\bar{p}$ collisions at $2E = 540$ GeV were observed in 1981 [106]; by the end of 1982 the collision rate was high enough to permit the observation of $W \rightarrow e\nu$ decays [107; 108]. In the following year the decays $Z^0 \rightarrow e^+e^-$ and $Z^0 \rightarrow \mu^+\mu^-$ were observed [109; 110]. For a detailed report see e.g. L. DiLella in ref. [111].

Here we shall limit ourselves to a brief description of the experiments and of the main results. Detectors at particle colliders consist, in general, of many successive layers of different kinds of detectors, surrounding the interaction region and aiming at a complete detection of all particles produced in the collision. Two detectors were designed and built at CERN for the $p\bar{p}$ collider.

The UA1 Collaboration, led by Carlo Rubbia built a complete detector [112] consisting of a central tracking detector in a strong magnetic field of 0.7T, an electromagnetic calorimeter, a hadronic calorimeter and a muon detector, all with large angular coverage. The importance of the hermeticity of the detector for the energy flow measurements emerged during the early analysis [112]; it permitted the detection of missing transverse energy carried away by a neutrino which remains of course undetected. In this way the 2 body decay of the W into $e^+\nu$ could be recognized and the W mass of about 80 GeV reconstructed. The second detector was built by the UA2 Collaboration [113] led by Pierre Darriulat. It had full calorimetric coverage over the polar angle interval $20^\circ < \Theta < 160^\circ$ but no muon detection and magnetic field in only part of the solid angle.

Figure 3.1 Layout of the three machines involved in the operation of the $p\bar{p}$ collider at CERN [111].

When searching for Z^0 particles the decay modes e^+e^- and $\mu^+\mu^-$ allowed direct determination of the Z mass by measuring the energies of the two leptons and the angle between their directions. Early results [107; 108] which established the existence of the intermediate bosons are shown in figures 3.2 and 3.3.

Among the properties of the intermediate boson W it is its spin $J = 1$ which is most intimately related to its presumed role as the mediator particle of weak interaction. As a consequence of the V-A coupling, the helicity of the quarks and antiquarks which fuse to form the W is -1 and +1, respectively, and the W spin is polarized in the direction of the $\bar{p}$ beam. Helicity arguments applied to the decay $W \rightarrow e\nu_e$ predict that the leptons (e^- or ν_e) should be preferentially

Figure 3.2 Early results of the UA1 Collaboration at CERN [4] establishing the existence of the intermediate W boson.

Figure 3.3 Early results of the UA1 Collaboration establishing the existence of the Z^0 boson [6].

Figure 3.4 Angular distribution of electrons from $W \rightarrow e\nu$ decays with respect to the $\bar{p}$ beam direction demonstration that the W has spin one (from UA1 [11]).

emitted opposite to the W polarization direction, and antileptons (e^+ or $\bar{\nu}_e$) along it. The observed angular distribution of electrons with respect to the $\bar{p}$ beam [114] is shown in figure 3.4. It has been shown by Maurice Jacob [115] that the mean value of $\cos\Theta^*$ is directly related to the W spin J :

$$\langle \cos\Theta^* \rangle = \langle \lambda \rangle \langle \mu \rangle / J(J+1)$$

where λ and μ are the total helicities of the initial $q\bar{q}$ and of the final $e\nu$ states, respectively. The value measured by the UA1 Collaboration [114]

$$\langle \cos\Theta^* \rangle = 0.43 \pm 0.07$$

demonstrated that the W spin is one and that the initial and final fermion states have maximal helicity, $\langle \lambda \rangle = \langle \mu \rangle = \pm 1$.

Table 3. Values of m_W and m_Z from measurements by UA1 and UA2 and predicted from neutrino scattering experiments.

	experiment	reference	predicted
m_W (GeV)	$80.8 \pm 0.4 \pm 0.8$ (scale)	[111]	80.2 ± 1.1
m_Z (GeV)	$90.9 \pm 0.3 \pm 0.2$ (scale)	[111]	91.6 ± 0.9

Later, more precise values of the masses were measured and confronted with the Standard Model predictions derived from precise measurements of $\sin^2 \Theta_W$ from deep inelastic neutrino scattering (see Table 3). The quantitative success of predicting the Fermi mass scale has been one of the triumphs of the Glashow-Salam-Weinberg theory and also of CERN's contributions to the study of the weak interaction. The outstanding contributions of Carlo Rubbia and of Simon van der Meer were rewarded by the 1984 Nobel Prize of Physics.

IV. CP violation

IV.1 Discovery of $K_L \rightarrow \pi^+ \pi^-$ decays : CP violation or alternative explanations?

The phenomenon of CP violation in decays of neutral K^0 mesons was discovered by Christenson, Cronin, Fitch and Turlay [116] in 1964 at the Brookhaven National Laboratory. They were studying the phenomenon of K_1^0 regeneration from a beam of K_2^0 . This phenomenon is one of the consequences of the strangeness oscillation scheme of K^0 and $\bar{K}^0$ worked out by Gell-Mann and Pais [117]. It is predicting two components, K_1 and K_2 with short and long lifetimes respectively. The set-up of the Princeton group was composed of two magnetic spectrometers for detecting the two-pion decay of K_1^0 . Sparkchambers were used to track the pions through the spectrometers. The tungsten regenerator was placed in a Helium filled bag to minimize interactions of K_2^0 . To check the background from decays in Helium they removed the regenerator. Some events which were compatible with $K_1^0 \rightarrow \pi^+ \pi^-$ decays remained. Which phenomenon could produce K_1^0 in Helium? The authors took nearly one year trying to eliminate those events or to understand their origin.

In their publication [116] they wrote "The events from the gas appear identical with those from the coherent regeneration in tungsten in both mass and angular spread" and concluded that K_2^0 decays to two pions with a branching ratio

$$R = (K_2^0 \rightarrow \pi^+ \pi^-) / (K_2^0 \rightarrow \text{all charged modes}) = (2.0 \pm 0.4) \cdot 10^{-3}.$$

They emphasized that any "alternative explanation required highly nonphysical behavior of the three-body decays of the K_2^0 . The presence of the two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP but requires an admixture of a CP even amplitude of $|\epsilon| \approx 2 \cdot 10^{-3}$."

From the experimental point of view confirmation was of course required and some improvements in the detection scheme allowing to eliminate the "alternative explanations". The first confirmation came from Europe. A group at CERN [118] led by Klaus Winter and Marcel Vivargent (Orsay) set out

- (1) to search for $K_2 \rightarrow \pi^+ \pi^-$ decays in vacuum, as the preceding experiment had been done in Helium, and to identify the decay particles, using a Cerenkov counter and an iron absorber, and
- (2) to search for an energy dependence of the two-pion decay rate.

They confirmed the result of Cronin and Fitch and eliminated the "alternative explanations" due to anomalous behavior of the three-body decays of the K_2^0 .

This fast action at CERN (six months between the publication of Cronin-Fitch and the submission of the paper from CERN) was made possible by Victor Weisskopf granting special priorities to the setting up of the detector. The sparkchamber pictures were analysed by a computer-assisted flying spot device which had been built at Orsay by P. Scharff-Hansen and collaborators under the leadership of Marcel Vivargent. This new technique enabled the group to perform the analysis in a record time.

If the two-pion decay of the K_2^0 was induced by a new weak and long-range cosmological field as hypothesised by Bell [119] and by Bernstein et al. [120], a branching ratio of $1.6 \cdot 10^{-1}$ instead of $2 \cdot 10^{-3}$ would have been observed for the mean K_2^0 momentum of 10 GeV/c at CERN compared to 1.1 GeV/c at Brookhaven. This increase was not found. Physics Today [121] published a sparkchamber picture of the CERN experiment on the front page and the head line : "Fifth force finished?" All alternative explanations were finally eliminated by the observation of quantum mechanical interference between the $K_2^0 \rightarrow \pi^+\pi^-$ amplitude and the amplitude of $K_1^0 \rightarrow \pi^+\pi^-$ from coherent regeneration. The interference phenomenon demonstrated unequivocally that the long-lived K_L^0 state contains an amplitude ε which is identical and indistinguishable from the $K_S^0 \rightarrow \pi^+\pi^-$ amplitude, and, hence $K_L^0 = \varepsilon K_1^0 + K_2^0$, or $K_2 \rightarrow 2\pi$ directly.

Val Fitch reported at the 1966 International Conference on High Energy Physics in Berkeley [122] on two types of experiments which were successful in demonstrating this interference phenomenon. One had been done by his own group [123]. They distributed regenerator material over the decay volume of their detector to obtain roughly equal amplitudes of regenerated $K_S^0 \rightarrow \pi^+\pi^-$ and of $K_L^0 \rightarrow \pi^+\pi^-$ decays. The other results came from the CERN-Orsay group of Winter and Vivargent [124] and from a CERN group led by Rubbia and Steinberger [125]. They measured the time dependence of two-pion decays behind regenerators of different thickness and obtained the relative phase and the beat frequency of the two amplitudes which is proportional to the K_S^0 - K_L^0 mass difference. While the method of Fitch was very robust, that of the CERN groups was more delicate but gave much higher precision. The interference term unfolded from the CERN-Orsay experiment (see figure 4.1) was shown in the talk of Fitch to demonstrate the power and the beauty of the method.

A first estimate of the phase of the ratio of $K_L^0 \rightarrow \pi^+\pi^-$ and $K_S^0 \rightarrow \pi^+\pi^-$ amplitudes, φ_{+-} was obtained in these experiments, which did not disagree with the expectation for a large class of models which can be characterized as "weak CP" models, independent of the details of the models. In the case of the so-called superweak interaction model proposed by Wolfenstein [126] an exact prediction can be made. In his talk at the 1966 Berkeley Conference [127], T.D. Lee said : "The superweak interaction has a certain appeal, because, then, we do not have to think anymore". CP noninvariance was the unavoidable conclusion.

Figure 4.1 Observed time dependence of the interference between $K_S^0 \rightarrow \pi^+\pi^-$ and $K_L^0 \rightarrow \pi^+\pi^-$ amplitudes behind a regenerator unfolded from data of the CERN-Orsay experiment [124].

But no understanding of how and why this effect occurred and was so small was achieved since its discovery.

The other question facing the 1966 Berkeley Conference and reported by Fitch [122] was whether or not the CP nonvariance observed in K^0 decay is limited to the weak interactions. A number of clashing experimental results concerning the η^0 decay had been reported. Friedberg, Lee and Schwartz [128] had suggested that the decay $\eta^0 \rightarrow \pi^+\pi^-\pi^0$ would be a good test for C violation in the electromagnetic or strong interactions. As a signature of a violation an asymmetry of the average energy of π^+ and π^- should appear. This can be expressed as an asymmetry in the Dalitz plot of event numbers of the right- and left-hand sides,

$$A = (N_R - N_L)/(N_R + N_L) .$$

A value of $A = +(7.2 \pm 2.8)\%$ had been reported by a Columbia-Stony-Brook bubble chamber experiment [129] lead by Paolo Franzini from Columbia University and interpreted as evidence for charge-conjugation noninvariance in the decay of the η^0 meson.

A CERN-Saclay-Zürich group led by G. Finocchiaro performed a counter-spark-chamber experiment at CERN [130]. This type of experiment, in general, has more possibilities for asymmetric biases than bubble chamber experiments. However, because of the larger statistics and the previous experience of the group with analysis of cloud chamber data on K^0 decays, more checks were accessible to the experimenters. "In this case", Fitch reported [122], "the experiment has obviously been carefully performed and the data treated in a meticulous fashion". The mass resolution of the instrument was better than that of the

bubble chamber and the background therefore substantially lower. The experiment gave a result compatible with no asymmetry and a much smaller error,

$$A = +(0.3 \pm 1.1)\% ,$$

at variance with Franzini's result and in support of C invariance in η^0 decay.

However, Fitch concluded, if C invariance were violated in η^0 decay, one would expect, on theoretical grounds, an asymmetry of less than 1% and that question therefore remained open. Later, in 1974, a Rutherford-Westfield College-Sussex group reported [131] on a new experiment, performed at the NIMROD Proton Synchrotron which confirmed the earlier result with an improved error of 0.25%.

There remains, even today, one other experimental search for T violation outside the weak interaction. This is a search for an electric dipole moment of the neutron which is being conducted by Ramsay, and by Lobachov and collaborators. However, at the time of writing this report, no positive effect has been reported. The present limit is $d < 12 \cdot 10^{-26}$ e.cm (95% CL) [132].

IV.2 Other manifestations of CP noninvariance

Two other manifestations of CP noninvariance in K^0 decays are possible, an asymmetry of the rates of the decays $K_L^0 \rightarrow \pi e \nu_e$ and $K_L^0 \rightarrow \pi \mu \nu_\mu$ according to the electric charge of the pion, and K_L^0 decay into $2\pi^0$. The value of the asymmetry in $K_L^0 \rightarrow \pi e \nu_e$ decays depends on the validity of the $\Delta S/\Delta Q$ rule (see chapter 5) and on the real part of the CP even admixture in long-lived neutral kaons, $\text{Re}\epsilon$. The rate of $K_L^0 \rightarrow 2\pi^0$ decays can give, in principle, when compared to decays to $\pi^+\pi^-$, decisive information on the question of direct CP violation in the $K^0 \rightarrow \pi\pi$ amplitudes of different isospin.

The existence of a charge asymmetry of the $K_{\mu 3}$ and $K_{e 3}$ decay modes was first demonstrated in two counter experiments at the 30 GeV Proton Synchrotron of Brookhaven National Laboratory, under the leadership of M. Schwartz [133] and J. Steinberger [134] respectively. The values found were smaller than the maximum, $2|\epsilon|$, approximately one-half that value, implying that the CP even admixture ϵ of K_L^0 has a non-zero imaginary part or more generally that the long-lived and short-lived K^0 states are not orthogonal.

A measurement of the charge asymmetry behind a regenerator can also determine the phase of the K_S^0 regeneration amplitude. This method was pioneered by the CERN-ORSAY [135] group but quantitative results were obtained by the Brookhaven group of Steinberger [136]. Combining this knowledge with the results of the interference experiments of $K^0 \rightarrow \pi^+\pi^-$ decay amplitudes behind a regenerator gave a more reliable but not more accurate estimate of the phase ϕ_{+-} .

The decay $K_L^0 \rightarrow \pi^0\pi^0$ turned out to be much more difficult to observe and to measure because of the difficulty of combining the needs of kinematical reconstruction, in particular the direction of the four photons from π^0 decays, with good detection efficiency. In 1968, at the 14th International Conference on High Energy Physics at Vienna, J.W. Cronin described the situation with the following words [137] : "At this conference a spectrum of results on $K_L^0 \rightarrow \pi^0\pi^0$ has been presented which range from a maximum of $|\eta_{00}| \cdot 10^3 = 4.3$ down to zero". He concluded by saying "the existence of the CP violating decay $K_L^0 \rightarrow \pi^0\pi^0$ is now established. However, the important question remains unanswered, is η_{00} different from η_{+-} ?".

IV.3 Precision experiments

Following the first demonstrations that the decay $K_L^0 \rightarrow \pi^0\pi^0$ indeed occurs [137] new experimental efforts led to consistent and precise results.

A CERN-ORSAY-RUTHERFORD group detected all four photons from $K_L^0 \rightarrow 2\pi^0 \rightarrow 4\gamma$ decay in thick plate sparkchambers (borrowed from the first CERN neutrino experiment) and determined their direction from the pairs produced and their energy by spark counting. They observed interference of K_L^0 and $K_S^0 \rightarrow 2\pi^0$ amplitudes behind a regenerator [138] and determined the absolute value and the phase of η_{00} . The authors performed [139] a phenomenological analysis of their results and those obtained on η_{+-} .

They decomposed the $K^0 \rightarrow 2\pi$ amplitudes into a T violating and CPT conserving part and a CPT violating and T conserving part. The data clearly established T invariance violation at a 10σ level while no evidence for CPT violation was found. However, the important question : "is η_{00} different from η_{+-} ", remained without answer.

An AACHEN-CERN-TORINO group [140] designed a new detector guided by the idea of measuring accurately the energies of all four γ rays and the direction of at least two γ 's of the four from $K_L^0 \rightarrow \pi^0\pi^0 \rightarrow 4\gamma$ decay. The upstream part of the detector was the direction-measuring region with their converter foils and sparkchambers while in the downstream part the remaining γ 's are converted and their energies measured in total absorption leadglass counters (see figure 4.2). This approach gave results of higher precision.

The use of the new technique of multi-wire proportional chambers invented by Charpak [141] improved the position resolution and made a revolutionary change in the data analysis. Track positions were recorded electronically at the time of the experiment, the time consuming measurements of spark positions from films, either manually or by flying spot techniques, became obsolete.

Figure 4.2 Apparatus of the Aachen-CERN-Torino group for the measurement of the $K_L^0 \rightarrow 2\pi^0$ decay rate [140].

Figure 4.3 New type of detector for K^0 decays using multiwire proportional (Charpak) chambers built by a CERN-Heidelberg group [142], (a) side view, (b) top view.

A CERN-Heidelberg group led by Jack Steinberger recognized the power of this new technique and built a new detector for K^0 decays [142] using these multiwire proportional chambers (see figure 4.3). A vast increase of statistics resulted in a corresponding improvement in precision.

In order to be free of the complications of regenerators and of the phase of regeneration Rubbia and Steinberger [143] proposed a new technique. In proton collisions with a nuclear target an excess of K^0 mesons over $\bar{K}^0$ is produced. A K^0 state is a coherent superposition of K_S^0 and K_L^0 amplitudes. Because of their different lifetimes and 2π decay rates maximal interference occurs about 12-14 K_S^0 lifetimes away from the target. The phases of η_{+-} and η_{00} and their absolute values can therefore be directly determined with high precision. An example of such a high precision measurement is shown in figure 4.4.

Figure 4.4 Example of precise interference experiment using K^0 states produced by proton-nucleus interaction [143].

At the time of the 16th International Conference on High Energy Physics, Carlo Rubbia [144] concluded that data on η_{00} were now consistent and, when compared with those on η_{+-} , they excluded a large number of theoretical models proposed to explain CP violation. Only two classes of models survived, the so-called superweak model, postulating a very weak CP violating interaction with $\Delta S = 2$ [126] and milliweak models invoking a small part (10^{-3}) of the normal $\Delta S = 1$ weak interaction as the source of CP violation. No significant deviations from the prediction of the superweak CP violation theory

$$\eta_{+-} = \eta_{00} = \varepsilon$$

were observed and no theory of milliweak CP violation gave a reliable estimate of how much it would expect to differ with these predictions. It was therefore difficult to assess which precision was needed to confirm or reject either of the two possibilities.

In 1973 Kobayashi and Maskawa proposed a specific milliweak model within the Standard Model [145]. At the time of the discovery of CP violation, only 3 quarks were known, and there was no possibility of explaining CP violation as a genuine phenomenon of weak interactions. However, the picture changes if six quarks exist in nature. Then the quark mixing of Cabbibo can be extended to a 3×3 mixing matrix containing three mixing angles and a phase. CP violating weak amplitudes can be constructed invoking box diagrams with transitions between quark flavors and families. A necessary consequence of this model of CP violation is the non-equality of η_{+-} and η_{00} . This "direct CP violation" is due to so-called Penguin diagrams for $K^0 \rightarrow 2\pi$ decay with an amplitude ε' . The two models of CP violation differ significantly with respect to the value of ε' : the superweak model predicts $\varepsilon' = 0$, and therefore $\eta_{+-} = \eta_{00} = \varepsilon$, while in milliweak models one expects $\varepsilon' \neq 0$.

In the Kobayashi-Maskawa model the value of ε' can be estimated by inferring the magnitude of the mixing angles from other experiments. Typical values for the measurable quantity are [146]

$$\text{Re}(\varepsilon'/\varepsilon) = (1 - |\eta_{00}|^2/|\eta_{+-}|^2)/6 \sim (1-2) \cdot 10^{-3} .$$

A measurement of this quantity to this level of precision therefore becomes a challenge for our understanding of CP violation. A measurement of the double ratio

$$R = \frac{|\eta_{00}|^2}{|\eta_{+-}|^2} = \frac{\Gamma(K_L \rightarrow 2\pi^0)/\Gamma(K_L \rightarrow \pi^+\pi^-)}{\Gamma(K_S \rightarrow 2\pi^0)/\Gamma(K_S \rightarrow \pi^+\pi^-)}$$

to a precision of 0.5% or better is therefore required to distinguish the remaining two models of CP violation and to test the Standard Model prediction. At the time of writing this report, five precise experiments have reported results [147] with a mean value of

$$\text{Re}(\varepsilon'/\varepsilon) = (1.5 \pm 0.5) \cdot 10^{-3} .$$

This result is in good agreement with the range of presently available predictions within the Cabibbo-Kobayashi-Maskawa Standard Model. Further improvements on the experimental side are underway at CERN and Fermilab aiming at a precision of $\pm 0.2 \cdot 10^{-3}$ [148].

V. The weak hadronic current

V.1 Introduction

Around 1960 it had become quite evident that the notion of universality of the weak interaction could not be extended to strange particle decays, while in the decays of baryons and mesons without strangeness this concept worked well, except for a five percent discrepancy between G_μ and G_F , the Fermi coupling constants deduced from muon decay $\mu \rightarrow e\nu\bar{\nu}$ and $O^{14} \rightarrow N^{14*}e^-\bar{\nu}$ decay, respectively.

At the time of the 1962 High Energy Physics Conference held at CERN there was much discussion about the validity of the $\Delta S/\Delta Q = 1$ rule. Viki Weisskopf [149] discussed violations of the rule which were reported and showed a cartoon (figure 5.1) in this connection, illustrating the uneasiness in this matter.

In K meson decays the situation was particularly complicated. While no $\Delta S = -\Delta Q$ signal was seen in K_{e4} decays [150], a considerable fraction of $\Delta S = -\Delta Q$ decays had been reported in K_{e3} and $K_{\mu 3}$ decays [151]. In the baryon sector $\Delta S = +\Delta Q$ decays $\Lambda \rightarrow p e^- \bar{\nu}_e$ and $\Sigma^- \rightarrow n e^- \bar{\nu}_e$ were observed with rates [152] which were about twenty times smaller than those predicted by the simplest extension of the universal weak interaction. How could the cherished idea of universality be saved?

Figure 5.1 Cartoon shown by V.F. Weisskopf [149] at the 1962 High Energy Physics Conference in connection with possible violations of the $\Delta S/\Delta Q$ rule.

The idea of baryon octets and decuplets and meson octets as manifestations of an approximate flavour SU(3) invariance of the strong interactions was introduced by Gell-Mann and Ne'eman [153] in 1961. Attempts to introduce these ideas into the classification of weak hadronic currents met with two vital problems : (1) to what extent does the $\Delta S = +\Delta Q$ rule hold in strangeness changing leptonic hyperon and meson decays? (2) Do the $\Delta S = 0$ leptonic decays of Σ hyperons have a rate comparable to that predicted by the universal weak interaction or are they also suppressed by an order of magnitude?

Answers to these questions came out of close collaboration between experiments at CERN and Nicola Cabibbo who spent the year 1962-63 at CERN.

The 28 GeV CERN Proton synchrotron (PS) opened the new experimental possibility to build an intense separated beam of K^- that stopped in a hydrogen bubble chamber. Stopping K^- mesons are a beautiful source of $\Sigma^\pm$ hyperons through the reactions

$$K^- p \rightarrow \Sigma^\pm \pi^\mp .$$

Such a beam was built in the new North hall of the PS allowing a short distance from the target to the bubble chamber to minimize the loss of K^- mesons by decays in flight. CERN designed and built electrostatic separators [154]. The 81 cm hydrogen bubble chamber of Saclay and Ecole Polytechnique Paris was moved

from the South hall into this beam and took data starting in December 1962. Already in a test run one event of the $\Delta S = 0$ leptonic Σ hyperon decay $\Sigma^- \rightarrow \Lambda e^- \bar{\nu}_e$ had been observed. A team from CERN with H. Courant and W. Willis as visitors and the Maryland University bubble chamber group led by G. Snow collaborated on the analysis of the $\Delta S = 0$ and $\Delta S = 1$ leptonic decays of Σ hyperons and reported first results at the Washington Meeting of the American Physical Society in April 1963 [155]. Final results were published in 1964 [156]. Ten events of the rare $\Delta S = 0$ decay $\Sigma^- \rightarrow \Lambda e^- \bar{\nu}_e$ were found and many examples of $\Delta S = +\Delta Q$ $\Sigma^- \rightarrow n e^- \bar{\nu}_e$ and $\Sigma^- \rightarrow n \mu^- \bar{\nu}_e$ decays but no definite example of $\Delta S = -\Delta Q$ Σ^+ decays.

N. Cabibbo used these results to develop the ideas published in his famous paper "Unitary Symmetry and Leptonic Decays" [157] (received 29 April 1963). He assumed that the weak current of strongly interacting particles J_μ transforms according to the eightfold representation of SU(3), and "neglected currents with $\Delta S = -\Delta Q$, or $\Delta I = 3/2$, which should belong to other representations" if they existed. He also assumed that the vector part of the current is in the same octet as the electromagnetic current. For $\Delta S = 0$ processes this assumption is equivalent to vector current conservation in the V-A theory for weak interactions [158]. This assumption was supported by the results on the rate of pion beta decay $\pi^+ \rightarrow \pi^0 e^+ \nu$ as compared to the rate of O^{14} beta decay [2].

Together with the octet of vector (V) currents, j_μ , he assumed an octet of axial vector (A) currents, g_μ . In each of these octets there is a current with $\Delta S = 0$ (no change of strangeness), and a current with $\Delta S = \Delta Q = 1$, and hence

$$J_\mu = a(j_\mu^{\Delta S=0} + g_\mu^{\Delta S=0}) + b(j_\mu^{\Delta S=1} + g_\mu^{\Delta S=1}) .$$

The usual, strong form of universality which failed to describe $\Delta S = 1$ decays would correspond to $a = b = 1$. Cabibbo introduced a weaker form of universality by requiring that J_μ has "unit length", i.e. $a^2 + b^2 = 1$ and $a = \cos\Theta$, $b = \sin\Theta$. This hypothesis implies that

$$G_F = G_\mu \cdot \cos \Theta ,$$

thus linking the small difference between G_F and G_μ to the small strangeness changing amplitude. On the other hand, since J_μ as well as the baryons and the pseudoscalar mesons belong to the octet representation of SU(3), one obtains relations between processes with $\Delta S = 0$ and $\Delta S = 1$. Cabibbo estimated the value of Θ from a comparison of the rates for $K^+ \rightarrow \mu^+ \nu$ and $\pi^+ \rightarrow \mu^+ \nu$, and obtained $\Theta = 0.257$.

For baryons in the SU(3) octet the axial vector matrix element could then be expressed as a function of two parameters, F and D, corresponding to the two ways (odd and even) of forming an octet out of $(8) \times (8)$. The two $\Delta S = 0$ processes, $n \rightarrow p e^- \bar{\nu}_e$ and $\Sigma^- \rightarrow \Lambda e^- \bar{\nu}_e$, could then be used to determine the values of F and D; together with the value of Θ and vector current conservation ($D^V =$

0) this allows to predict the rates of all three $\Delta S = +\Delta Q$ transition for which data existed. It worked !

A plot in the publication of the CERN data [156], (see figure 5.2) displays how well the available hyperon semileptonic decay data agreed with the Cabibbo hypothesis.

Figure 5.2 A plot of allowed values of F and D showing the constraints on the Cabibbo theory imposed by the various measurements. The shaded bands indicate the experimental errors. The data shown are from the hyperon beam experiment at the CERN SPS [163]. Earlier experiments [156] did show already agreement with the theory.

The subsequent development is marked by further and more precise experimental studies of hyperon decays using electronic techniques and a hyperon beam (Chapter V.2). Cabibbo's choice of neglecting $\Delta S = -\Delta Q$ currents was fully justified by further experimental work on kaon decays (Chapter V.3) which established the validity of the rule at the 1% level.

Finally, the extension of the Cabibbo theory to six quarks by Kobayashi and Maskawa [159] will briefly be described in Chapter V.4.

V.2 Experimental studies of hyperon decays

While the early experiments which led to the basic assumptions of the Cabibbo theory were performed in bubble chambers, further tests of the theory and improved precision came from electronic counter experiments [160]. At CERN these experiments were pioneered by a CERN-Heidelberg group led by Heintze and Soergel. They designed an experimental set-up which allowed to detect electrons from hyperon beta decays and to discriminate them from pions by

using a large focusing Cerenkov counter [161], tracks were measured using wire chambers. The main advantage over bubble chamber techniques was the trigger which selected events of the reaction

$$K^- p \rightarrow \Xi^- K^+$$

by requiring a backwards going K^+ and a Ξ decay to an electron in coincidence. The set-up, shown in figure 5.3, was operated in an enriched K^- beam of 1.65 GeV/c momentum. At each cycle of the accelerator 7000 K^- and 100'000 π^- crossed the detector without problems of event superpositions owing to the short sensitive time of microseconds of sparkchambers compared to the millisecond sensitivity of bubble chambers.

The first experiment performed by the CERN-Heidelberg group [161] managed to log 17 events of $\Xi^- \rightarrow \Lambda(\Sigma^0) e^- \bar{\nu}_e$ and gave a branching ratio of $(6.8 \pm 2.2) \cdot 10^{-4}$ in good agreement with the prediction of the Cabibbo theory ($6 \cdot 10^{-4}$) derived from other hyperon decays.

Figure 5.3 Experimental set-up for studying $\Xi^- \rightarrow \Lambda e^- \bar{\nu}_e$ and $\Lambda \rightarrow p e^- \bar{\nu}_e$ beta decay at the CERN PS [161]. The Ξ^- and its decay products are observed in the optical spark chamber SP_3 . T is a focusing Cerenkov counter to discriminate between electrons and pions. Counters 1-6 and M_1 - M_{17} are plastic scintillators, C_1 a high pressure ethylene Cerenkov counter for π -suppression, C_2 a FC75 liquid Cerenkov counter and C_3 is a cylindrical plexiglass Cerenkov counter. The tracks of the incoming K^- and the outgoing K^+ are localized in the wire chambers SP_1 , SP_2 and in the cylindrical wire chambers SP_4 , which have magnetostrictive readout. The target region is shown in detail in the upper left corner.

Several experiments studied extensively the decay $\Lambda \rightarrow p e^- \bar{\nu}_e$ during the pre-hyperon beam era. We refer here to another experiment performed at CERN by the CERN-Heidelberg group [162] using the reaction $\pi N \rightarrow \Lambda K$ just below the ΣK threshold ($p_\pi \sim 1.1$ GeV/c) as a source of polarized Λ . The detector was the same as that used for studying Ξ^- beta decay [12]. About a thousand Λ beta decay events were observed, and the decay rate and the asymmetry parameters α_e , α_p and α_ν of the angular distributions with respect to the Λ spin were measured as well as the electron-neutrino angular correlation. Good agreement with the Cabibbo model was found and no deviations from the underlying V-A theory, e.g. no second class current, no time reversal violation nor S or T contributions.

The construction of hyperon beams, first at the AGS of Brookhaven National Laboratory and the CERN PS, and more recently at the CERN SPS has given the next advance in the field of hyperon beta decay studies. High statistics experiments, with 10^3 to 10^4 events and up to 10^5 events in the case of the $\Lambda \rightarrow p e^- \bar{\nu}_e$ decay, have been performed.

Hyperon beams are secondary beams of particles, produced by striking a target with the primary proton beam of the accelerator. In the case of negative beams they contain Σ^- , Ξ^- and Ω^- hyperons and a background of π^- . The beam built at the CERN SPS [163] is shown in figure 5.4. The main design problem is the short decay length of the hyperons. For example, at 100 GeV/c the decay lengths of Σ^- , Ξ^- and Ω^- are 3.7m, 3.7m and 1.5m, respectively. Therefore, the beam has to be as short as possible. Fluxes of 5000 Σ^- and 500 Ξ^- hyperons per pulse

Figure 5.4 Plan view of the apparatus of the CERN SPS hyperon beam experiment [163]. He : helium bags; Li : Lithium radiators; Xe : Xenon proportional chambers; DC : drift chambers.

have been achieved. These hyperons were identified by a compact Cerenkov counter (DISC) developed at CERN. A decay region of 10m length was followed by a magnetic spectrometer and electron identification devices, a lead glass array, a Cerenkov counter and transition radiation counters. Multiwire proportional chambers and drift chambers were used to measure tracks.

The results of these studies have been analysed in the frame work of the Cabibbo theory in terms of three parameters Θ , F and D (see chapter 5.1). We give here the results from the CERN hyperon decay experiment based on five hyperon beta decays [160]. The q^2 dependence of the form factors and radiative corrections have been included in the analysis and give a completely consistent picture for the following values

$$F = 0.477 \pm 0.012$$

$$D = 0.756 \pm 0.011$$

$$\sin\Theta = 0.231 \pm 0.003 \quad .$$

To what extent the different decays constrain these results is shown in figure 5.2. The widths of the bands are indicating the experimental errors; they overlap in a common region as predicted by the Cabibbo theory.

For the beta decay of the Σ^- hyperon, $\Sigma^- \rightarrow n e^- \bar{\nu}_e$, the Cabibbo theory, based on the other hyperon decay data, is predicting a ratio of form factors $g_A/g_V = -0.28 \pm 0.02$. Earlier experiments had given a positive sign [160], but a more recent experiment [164], performed at FNAL near Chicago, has obtained a beam of polarized Σ^- hyperons of 250 GeV/c momentum derived at an angle of 3 mrad. From a sample of 90'000 decays they determined, experimentally, $g_A/g_V = -0.327 \pm 0.02$, in excellent agreement with the prediction, and equivalently, an up-down asymmetry of the angular distribution of electrons with respect to the Σ spin polarization of $\alpha_e = -0.53 \pm 0.14$.

V.3 The $\Delta S/\Delta Q$ rule in kaon decays

Following the wise attitude of Cabibbo to neglect early evidence for $\Delta S = -\Delta Q$ decays [165, 166] and in view of the success of his model [157] in describing hyperon beta decay there was new interest to establish the limits of validity of the $\Delta S = \Delta Q$ rule with higher precision. Such limits can only be determined in a study of semileptonic decays of neutral kaons, K^0 and $\bar{K}^0$. Studies of K_{e4} decays [171] $K^+ \rightarrow \pi^+ \pi^+ e^- \bar{\nu}$ which violate the rule can only be used to search for events of the $\Delta S = -\Delta Q$ type; however if none is found they do not determine the limits of validity of the $\Delta S = \Delta Q$ rule.

In neutral kaon decays we can have $\Delta S = \Delta Q$ decays, $K^0 \rightarrow \pi^- e^+ \nu_e$ and $\bar{K}^0 \rightarrow \pi^+ e^- \bar{\nu}_e$ and $\Delta S = -\Delta Q$ decays, $K^0 \rightarrow \pi^+ e^- \bar{\nu}_e$ or $\bar{K}^0 \rightarrow \pi^- e^+ \nu_e$.

Early bubble chamber experiments [165, 166] performed in the Ecole Polytechnique (Paris) heavy liquid bubble chamber at CERN had indicated a sizeable violation

of the rule. C. Rubbia had summarized [167] the combined results by stating that they were implying the existence of $\Delta S = -\Delta Q$ currents at the 15% level compared with the octet, $\Delta S = +\Delta Q$ currents; the evidence had a 3 standard deviation statistical significance.

A new study of these decay modes was performed by a CERN-ORSAY-VIENNA Collaboration at CERN [168] led by K. Winter and M. Vivargent. They produced an initially pure K^0 state in the inelastic charge exchange reaction

$$K^+p \rightarrow K^0p\pi^+$$

using an enriched K^+ beam of 2.4 GeV/c momentum.

The initial K^0 state is propagating by the weak interaction eigenstates K_S^0 and K_L^0 and an amplitude of $\bar{K}^0$ is building up as a function of the eigentime τ elapsed since the K^0 production. Using the notation

$$N^+ = N(\pi^- e^+ \nu)$$

$$N^- = N(\pi^+ e^- \bar{\nu})$$

and the ratio of $\Delta S = -\Delta Q$ to $\Delta S = \Delta Q$ amplitudes x , one is expecting the decay rates varying as a function of eigentime τ in the form

$$N^\pm(\tau) \sim \frac{1}{2} \left[|1+x|^2 e^{-\Gamma_S \tau} + |1-x|^2 e^{-\Gamma_L \tau} \right. \\ \left. \pm 2(1-|x|^2) \cos \Delta m \tau e^{-\Gamma \tau} - 4 \operatorname{Im} x \sin \Delta m \tau e^{-\Gamma \tau} \right],$$

where $\Delta m = m_L - m_S = 0.54 \cdot 10^{10} \text{ s}^{-1}$ is the difference of the K_L^0 and K_S^0 masses, Γ_L and Γ_S are the K_L^0 and K_S^0 decay rates and $\Gamma = \frac{1}{2}(\Gamma_L + \Gamma_S)$.

The momentum of the initial K^0 state was determined from the kinematics of the reaction $K^+p \rightarrow K^0p\pi^+$. The directions of the p and π^+ were measured in a cylindrical spark chamber set-up surrounding the hydrogen target (see figure 5.5) and the charged decay products of K^0 were analysed in a magnetic spectrometer. One of the decay products can be an electron; the other is a pion. Electrons were identified in a large 14-cell Cerenkov counter; their charge was determined by the magnet spectrometer. The time distribution of a sample of 4778 $K^0 \rightarrow \pi e \nu$ events is shown in figure 5.6. It shows excellent agreement with the expected evolution of K^0 and $\bar{K}^0$ states in the strangeness oscillation scheme predicted by Gell-Mann and Pais [169] and no evidence for weak hadronic currents with $\Delta S = -\Delta Q$ at the 2% level. A result of similar precision was obtained for the real part of x from a measurement of the charge asymmetry in $K_L^0 \rightarrow \pi e \nu$ decays in an electronic experiment by S. Bennett et al. [170] which was discussed in Chapter III.

A new high statistics search for $\Delta S = -\Delta Q$ $K^+ \rightarrow \pi^+ \pi^+ \ell^- \nu$ decays was performed in another electronic experiment at CERN by a Geneva-Saclay group [171] led by R. Mermod and R. Turlay and again, found no evidence.

Figure 5.5 Plan view and elevation of apparatus used to detect the production of the initial K^0 state and its subsequent decay into different modes [168].

A detailed review of kaon decays by Chounet et al. [172] helped to clarify the situation. Further evidence for the validity of the V-A theory for kaon decays came from measurements of the branching ratio

$$R = \frac{\Gamma(K^+ \rightarrow e^+ \nu)}{\Gamma(K^+ \rightarrow \mu^+ \nu)}.$$

The predicted value $R = 2.1 \cdot 10^{-5}$ for axial vector interaction was confirmed by an Oxford group [173] and with the highest precision by the CERN-Heidelberg group [174] at CERN who found $R = (2.45 \pm 0.11) 10^{-5}$.

These kaon decays are well described by stating, in addition, that the ratios

$$\Gamma(K^+ \rightarrow e \nu) / \Gamma(\pi^+ \rightarrow e \nu) \text{ and } \Gamma(K^+ \rightarrow \mu^+ \nu) / \Gamma(\pi^+ \rightarrow \mu^+ \nu)$$

are consistent with the value of $\sin \theta = 0.231$ derived from hyperon beta decays.

V.4 Generalization of the Cabibbo theory

While all leptons have the same weak coupling constant this is not so for different quark flavours. Cabibbo had introduced a linear combination of quark states as the weak interaction eigenstate that couples to the u quark with the universal strength. With the discovery of six quarks this quark mixing was generalized by Kobayashi and Maskawa [145]; they introduced a matrix V which describes this mixing by a unitary transformation of the mass eigenstates (d, s, b) into the weak interaction eigenstates (d', s', b') :

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Figure 5.6 Time distribution of observed decays in the $N^+(\pi^-e^+\nu)$ and in the $N^-(\pi^+e^-\bar{\nu})$ mode. Also shown is the prediction for $x = 0$, $\Delta S = \Delta Q$ decays [168].

This matrix can be parametrized by four parameters, three angles Θ_i and one CP violating phase δ [see Chapter IV]. Values of these parameters have been determined [175] from nuclear beta decay rates, from muon decay, hyperon beta decay and kaon decay rates; charm-quark couplings have been determined from measurements of single charm production in neutrino processes, yielding $|V_{ud}| = 0.9744 \pm 0.0010$ and $|V_{us}| = 0.2205 \pm 0.0018$ and in antineutrino induced reactions, yielding $|V_{cd}| = 0.21 \pm 0.03$. The coupling V_{cs} has been determined from the decay rate of $D^+ \rightarrow \bar{K}^0 e^+ \nu$ with the result $|V_{cs}| = 0.96 \pm 0.10$. The coupling ub can, in principle, be determined from the rate of direct quark decays $b \rightarrow ue^- \nu$, and the coupling cb from the lifetime of b quark hadrons and their semileptonic branching ratio.

Using these data and constraints one obtains a pattern with a hierarchy in which the mixing angle of the first two quark families, Θ_{12} is larger than that connecting the second and third generations, Θ_{23} , and this is again larger than Θ_{13} . This pattern remains to be explained by theories beyond the standard model, maybe in relation with the quark masses.

No experimental evidence for lepton mixing has been found until now [176], but mixing of the neutrino flavours cannot be excluded either. A search for this phenomenon remains one of the great challenges of experimental particle physics.

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References

- [1] T. Fazzini, G. Fidecaro, A.W. Merrison, H. Paul, and A.V. Tollestrup, Phys. Rev. Letters 1(1958)247
- [2] P. Depommier, J. Heintze, A. Mukhin, C. Rubbia, V. Soergel, and K. Winter, Phys. Letter 2(1962)23;
P. Depommier, J. Duclos, J. Heintze, K. Kleinknecht, H. Rieseberg, and V. Soergel, Nucl. Physics B4(1968)189
- [3] G. Backenstoss, B.D. Hyams, G. Knop, P.C. Marin, and U. Stierlin, Phys. Rev. 129(1963)2759
- [4] J.H. Christenson, J.W. Cronin, V.L. Fitch, and R. Turlay, Phys. Rev. Letters 13(1964)138
- [5] X. de Bouard, D. Dekkers, B. Jordan, R. Mermod, T.R. Willitts, and K. Winter, Phys. Letters 15(1965)58
- [6] H. Burkhardt et al., Phys. Lett. B206(1988)169
- [7] H. Wahl et al., CERN Proposal SPSC/90-22/P253, approved as NA 48
- [8] Simon van der Meer, CERN 62-16
- [9] For a review see : P. Musset and J.-P. Vialle, Neutrino Physics with Gargamelle, Physics Reports 39C(1978)1
- [10] T. Eichten et al., Physics Letters 46B(1973)274
- [11] S. van der Meer, CERN-ISR-PO 72-31(1972)
- [12] C. Rubbia, D. Cline, and P. McIntyre, Proc. Int'l. Neutrino Conference, ed. H. Faissner, H. Reithler, and P. Zerwas, Vieweg, Braunschweig (1977)p.683
- [13] UA1 Collaboration, C. Albajar et al., Z. Phys. C44(1989)15
UA2 Collaboration, J. Allitti et al., Z. Phys. C47(1990)11
- [14] P. Galison, Rev. Mod. Phys. 55(1983)477
- [15] F.J. Hasert et al., Phys. Letters 46B(1973)121
- [16] F.J. Hasert et al., Phys. Letters 46B(1973)138
- [17] J. Steinberger, CERN-EP/88-180

- [18] A. Benvenuti et al., Phys. Rev. Lett. 30(1973)1084
- [19] V.F. Weisskopf, The Joy of Insight, New York, Basic Books, 1991
- [20] M. Bott-Bodenhausen et al., Phys. Letters 24B(1967)194
- [21] M. Block et al., Phys. Letters 12(1964)281
- [22] W. Lee, Phys. Letters 40B(1972)423
- [23] J.S. Bell, J. Løvseth, and M. Veltman in Proc. Int'l. Conference on Elementary Particle Physics, Sienna 1963, ed. G. Bernardini, G. Puppi (Societa Italiana di Fisica, Bologna) Vol. 1, p. 555
- [24] G. 'tHooft, Nucl. Physics B33(1971)173
- [25] S.L. Glashow, J. Iliopoulos, and L. Maiani, Phys. Rev. D2(1970)1285
- [26] D.C. Cundy et al., Phys. Letters 31B(1970)478
- [27] S.L. Wu, Rapporteur Tal., Proc. Int'l. Symp. on Lepton and Photon Interactions at High Energies, Hamburg, ed. W. Bartel (1987)39.
- [28] M. Jonker et al., Phys. Lett. B107(1981)241.
- [29] H. Abramowicz et al., Phys. Lett. B109(1982)115.
- [30] CHARM Collab., J. Dorenbosch et al., Phys. Lett. B180(1986)303.
- [31] S.L. Glashow, Nucl. Phys. 22(1961)579; A. Salam and J. Ward, Phys. Lett. 13 (1963)168; S. Weinberg, Phys. Rev. Lett. 19(1967)1264.
- [32] K. Winter, Proc. Thirteenth Int'l. Conf. on Neutrino and Astrophysics, World Scientific, Singapore (1988)403.
- [33] J.V. Allaby et al., CHARM Collab., Phys. Lett. B231(1989)317.
- [34] C.Y. Prescott et al., Phys. Lett. B(1978)347; B84(1979)524.
- [35] M.A. Bouchiat et al., Phys. Lett. B134(1984)46 and M.A. Bouchiat and C.A. Picketty, J. Phys. (France)46(1985)1897.
- [36] M.C. Noecker et al., Phys. Rev. Lett. 61(1988)310.
- [37] U. Amaldi et al., Phys. Rev. D36(1987)1385.
- [38] G. Costa et al., Nucl. Phys. B297(1988)244,

- [39] G.L. Fogli and D. Haidt, Z. Phys. C40(1988)379.
- [40] J.E. Kim et al., Rev. Mod. Phys. 53(1981)211.
- [41] L.M. Seghal, Progress in Particle and Nuclear Physics
ed. A. Faessler, vol. 14, Pergamon Press (1981)1.
- [42] M. Holder et al., CDHS Coll., Phys. Lett. B72(1977)254
- [43] J.V. Allaby et al., CHARM Coll., Z. Phys. C38(1988)403
- [44] R.C. Allen et al., Phys. Rev. Letters 64(1990)330
- [45] C.Y. Prescott et al., Phys. Lett. B77(1978)347; B84(1979)524
- [46] M.A. Bouchiat et al., Phys. Lett. B134(1984)46
M.C. Noecker et al., Phys. Rev., Lett. 61(1988)310
- [47] P. Musset, J.-P. Vialle, Phys. Reports 39C(1978)59
- [48] H. Abramowicz et al., CDHS Collab., Phys. Rev. Letts. 57(1986)298
- [49] J.V. Allaby et al., CHARM Collab., Z. Phys. C36(1987)611
- [50] C.H. Llewellyn-Smith, Nucl. Phys. B228(1983)205
- [51] J.V. Allaby et al., CHARM Collab., Phys. Lett. B231(1989)317
- [52] G. 't Hooft, Phys. Lett. B37(1971)195
- [53] H. Faissner et al., Phys. Rev. Lett. 41(1978)213
- [54] J. Dorenbosch et al., CHARM Collab., Z. Phys. C41(1989)567
- [55] S.L. Wu, Proc. Int. Symp. Lepton and Photon Interactions at High
Energies, Hamburg, ed. W. Bartel (1987)39
- [56] F. Reines, H. Gurr and H. Sobel, Phys. Rev. Lett. 37(1976)315
- [57] G.H. Georgi and S.L. Glashow, Phys. Rev. Lett. 32(1974)438
- [58] see e.g. F. Dydak, Proc. Int. Conf. High Energy Physics, Singapore 1990
and J.R. Carter, Proc. Int. Conf. on Lepton-Photon Interactions at High
Energy, Geneva 1991

- [59] D. Geiregat et al., CHARM II Collab., Phys. Lett. B259(1991)499
and P. Vilain et al., Phys. Lett. B281(1992)159
- [60] D. Allasia et al., WA25 Collab., Nucl. Phys. B307(1988)1
- [61] N. Armenise et al., BEBC-TST Collab., Paper CO23, Neutrino 88,
Boston 1988
- [62] U. Amaldi et al., Phys. Rev. D36(1987)1385
- [63] P. Langacker, Proc. 24th Int. Conf. High-Energy Physics, Munich,
Springer Verlag (1988), p. 190
- [64] T.D. Lee, C.N. Yang, Phys. Rev. Lett. 4(1960)307
- [65] G. Danby et al., Phys. Rev. Letters 9(1962)36
- [66] M.M. Block et al., Phys. Lett. 12(1964)281
J.K. Bienlein et al., Phys. Lett. 13(1964)80
- [67] T. Eichten et al., Phys. Lett. 46B(1973)274
- [68] G. Bernardini et al., Phys. Lett. 13(1964)86
- [69] M.M. Block et al., Phys. Lett. 12(1964)281
- [70] J.G.H. de Groot et al., CDHS Collab., Z. Phys. C1(1979)143
- [71] M. Jonker et al., CHARM Collab., Z. Phys. C17(1983)211
- [72] D. Geiregat et al., CHARM II Collab., Phys. Lett. 247B(1990)131
- [73] M.M. Block et al., Phys. Lett. 12(1964)281
- [74] D. Perkins, Proc. 1963 Int. Conference on Elementary Particle Physics,
G. Bernardini, G. Puppi, ed., Societa Italiana di Fisica, Bologna, p.555
- [75] J. Bell, J. Løvseth and M. Veltman
Proc. 1963 Int. Conference on Elementary Particle Physics,
G. Bernardini, G. Puppi, ed., Societa Italiana di Fisica, Bologna, p.584
- [76] J. Bell, The 1963 NPA Seminars, The Neutrino Experiment,
C. Franzinetti, editor, CERN 63-37, (1963), p.1
- [77] D. Perkins, Proc. Topical Conference on Weak Interactions,
J. Bell, editor, CERN 69-7, (1969), p.1

- [78] K. Gottfried, Phys. Rev. Lett. 18(1967)1174
- [79] J. Steinberger, Proc. Europhys. Conf. High Energy Physics, Lund 1969, p. 41
- [80] J.D. Bjorken, Phys.Rev. 179(1969)1547
R.P. Feynman, Photon-hadron interactions (Benjamin, New York, 1972)
- [81] J.G.H. De Groot et al., CDHS Collab., Z.Phys. C1(1979)143
H. Abramowicz et al., CDHS Collab., Z.Phys. C12(1982), C17(1983)283
- [82] A. Benvenuti et al., Phys.Rev.Letters 36(1976)1478
- [83] A. Benvenuti et al., Phys.Rev.Letters 37(1976)189
- [84] B.C. Barish et al., Phys. Rev.Letters 39(1977)741, 1595
- [85] P. Berge et al., CDHS Collab., Z.Phys. C35(1987)443, Z.Phys. C49(1991)187
J. Dorenbosch et al., CHARM Collab., Z.Phys. C38(1988)403
- [86] M. Virchaux, A. Milsztajn, Phys. Lett. B274(1992)221
- [87] A. Bodek et al., Phys. Rev. D20(1979)1471
- [88] P. Musset, J.P. Vialle, Phys.Reports C39(1978)29
- [89] M. Gourdin, Nucl.Phys. B29(1971)601
- [90] O. Nachtmann, Nucl.Phys. B38(1972)397
- [91] C.H. Llewellyn-Smith, Phys.Reports 3C(1972)261
- [92] R. Feynman, Proceeding Neutrino '72
Europhysics Conference, Balatonfüred (Hungary)
(ed. A. Frenkel, G. Marx) vol. 11, p. 75
- [93] K. Schultze, Proc. XVI Int. Conf. High Energy Physics, Batavia - Chicago 1972, vol. 2, p.207
- [94] D. Perkins, Proc. XVI Int. Conf. High Energy Physics, Batavia - Chicago 1973, vol. 4, p.189
- [95] See e.g. in K. Winter, editor, Neutrino Physics, Cambridge Univ. Press 1992
- [96] D. Perkins, ref. [94]

- [97] C.H. Llewellyn-Smith, Nucl.Phys. B17(1970)277
- [98] P.C. Bossetti et al., Nucl. Phys. B142(1979)1
- [99] J.G.H. de Groot et al., CDHS Collab., Z.Phys. C1(1979)143
- [100] A. Benvenuti et al., Phys.Rev.Letters 34(1975)419
A. Rubbia, Proc. 1975 Int. Conf. on Lepton and Photon Interactions at High Energies.
Stanford Univ., W.T. Kirk, editor, p. 1049
- [101] M. Holder et al., CDHS Collab., Phys.Lett. 69B(1977)377
H. Abramowicz et al., CDHS Collab. Z.Phys. C15(1982)19
- [102] S.L. Glashow, J. Iliopoulos, L. Maiani
Phys.Rev. D2(1970)1285
- [103] C. Angelini et al., Phys.Lett. 84B(1979)150
- [104] C. Rubbia, P. McIntyre, and P. Cline
Proc. Int. Neutrino Conference, Aachen 1976, Vieweg, Braun-Schweig 1977
(ed. H Faissner, H. Reithler, P. Zerwas) p.683
- [105] S. van der Meer, CERN-ISR-PO 72-31(1972)
- [106] The staff of the CERN proton-antiproton project
Phys. Lett. 107B(1981)306
- [107] UA1 Collab., G. Arnison et al., Phys.Lett. 122B(1988)103
- [108] UA2 Collab., M. Banner et al., Phys.Lett. 122B(1983)476
- [109] UA1 Collab., G. Arnison et al., Phys.Lett. 126B(1983)398
- [110] UA2 Collab., P. Bagnaia et al., Phys.Lett. 129B(1983)130
- [111] L. DiLella, in Neutrino Physics, Cambridge Univ. Press 1992,
ed. K. Winter, p.445
- [112] UA1 Collab., A. Astbury et al., Phys. Scripta 23(1981)397
- [113] UA2 Collab., B. Mansoulié, Moriond Workshop, 1983 Edition
Frontières, p.609
- [114] UA1 Collab., C. Albajar et al., Z.Phys. C44(1989)15
- [115] M. Jacob, Nuovo Cimento 9(1958)826

- [116] J.H. Christenson, J.W. Cronin, V.L. Fitch and R. Turlay,
Phys. Rev. Lett. 13(1964)138
- [117] M. Gell-Mann, A. Pais, Phys. Rev. 97(1955)1387
- [118] X. de Bouard et al., Phys. Lett. 15(1965)58
- [119] J.S. Bell and J.K. Perring,
Phys. Rev. Letts. 13(1964)348
- [120] Physics Today, April 1965
- [121] J. Bernstein, N. Cabibbo and T.D. Lee,
Phys. Letts. 12(1964)146
- [122] V. Fitch, Proceedings Int. Conference on High Energy Physics,
Berkeley 1966, p.63
- [123] V. Fitch, R. Roth, J. Ross and W. Vernon,
Phys. Rev. Lett. 15(1965)73
- [124] M. Bott-Bodenhausen et al., Phys. Lett. 20(1966)212
- [125] C. Alff-Steinberger et al., Phys. Lett. 20(1966)207
- [126] L. Wolfenstein, Phys. Rev. Lett. 13(1964)562
- [127] T.D. Lee, Proc. Int. Conf. on High Energy Physics, Berkeley 1966, p.75
- [128] R. Friedberg, T.D. Lee, M. Schwartz (unpublished)
J. Bernstein, G. Feinberg, T.D. Lee, Phys. Rev. 139(1965)B 1650
- [129] C. Baltay et al., Phys. Rev. Lett. 16(1966)1224
- [130] A.M. Cnops et al., Phys. Lett. 22(1966)546
- [131] J.M.R. Jane et al., Phys. Lett. 48(1974)260
- [132] Review of Particle Properties, Phys. Lett. 239B(1990)11.18
- [133] D. Dorfan et al., Phys. Rev. Lett. 19(1967)987
- [134] S. Bennett et al., Phys. Rev. Lett. 19(1967)993
- [135] M. Bott-Bodenhausen et al., Phys. Lett. 24B(1967)438
- [136] S. Bennett et al., Phys. Lett. 27B(1968)238

- [137] J.W. Cronin, Proc. Int. Conf. on High Energy Physics, Vienna 1968, p.280
- [138] J.C. Chollet et al., Phys. Lett. 31B(1970)658
- [139] K. R. Schubert et al., Phys. Lett. 31B(1970)662
- [140] M. Holder et al., CDHS Collab., Phys. Lett. 40B(1972)141
- [141] J.H. Dieperink et al., Proc. Int. Conf. on Instrumentation for High-Energy Physics, Dubna 1970, p.251
- [142] C. Geweniger et al., Phys. Lett. 48B(1974)487
- [143] A. Böhm et al., Phys. Lett. 27B(1968)321 and Nucl. Phys. B9(1969)605
- [144] C. Rubbia, Proc. 16h Int. Conf. High Energy Physics, Chicago and Batavia 1972, vol. 4 p.157
- [145] M. Kobayashi, T. Maskawa, Prog. Theor. Phys. 49(1973)652
- [146] see e.g. J.M. Gerard, Proc. Int. Conf. Lepton-Photon Interactions at High Energy, Geneva 1991
- [147] K. Kleinknecht, Comments on Nucl. Particle Physics, (to be published)
- [148] G.D. Barr et al., NA 48 experiment at CERN
- [149] V .F. Weisskopf, Proc. Int. Conf. on High-Energy Physics, Geneva 1962, p. 929
- [150] A Barbaro-Galtieri et al., Phys. Rev. Lett. 9(1962)26
- [151] G. Alexander et al., Proc. Int. Conf. on High-Energy Physics, Geneva 1962, p. 448
- [152] R.P. Ely et al., Proc. Int. Conf. on High-Energy Physics, Geneva 1962, p.445
- [153] M. Gell- Mann, Cal Tech Report CTSL-20, 1961 (unpublished)
Y. Ne'eman, Nucl. Phys. 26(1961)222
- [154] C. Germain, R. Tinguely, Proc. Int. Conf. on Instrumentation for High-Energy Physics, CERN-Geneva 1962, p. 21
- [155] W. Willis et al., Bull. Am. Phys. Soc. 8(1963)349
- [156] W. Willis et al., Phys. Rev. Letters 13(1964)291

- [157] N. Cabibbo, Phys. Rev. Letters 10(1963)531
- [158] R.P. Feynman and M. Gell-Mann, Phys. Rev. 109(1958)193
R.E. Marshak and E.C.G. Sundarshan, Phys. Rev. 109(1958)1860
- [159] M. Kobayashi, T. Maskawa, Prog. Theor. Phys. 49(1973)652
- [160] For a review see J.M. Gaillard and G. Sauvage, Ann. Rev. Nucl. Part. Sci. 34(1984)351
- [161] J. Duclos et al., Nucl. Phys. B32(1971)493
- [162] K.W. Althoff et al., Phys. Lett. 37B(1971)531, 537 and
Phys. Lett. 43B(1973)237
- [163] M. Bourquin et al., Z. Phys. C12(1982)307 1; C21(1983)1, 17 and 27
- [164] S.Y.H. Sueh et al., Phys. Rev. Lett. 54(1985)2399
- [165] B. Aubert et al., Phys. Lett. 17(1965)59
- [166] M. Baldo-Ceolin et al., Nuovo Cim. 38(1965)684
- [167] C. Rubbia, Proc. Topical Conf. Weak Interactions, CERN 69-7
- [168] F. Niebergall et al., CERN-ORSAY-VIENNA Collaboration,
Phys. Lett. 49B(1974)103
- [169] M. Gell-Mann, A. Pais, Phys. Rev. 97(1955)1387
- [170] S. Bennett et al., Phys. Lett. 29B(1969)317
- [171] M. Bourquin et al., Geneva-Saclay Collaboration,
Phys. Lett. 36B(1971)615
- [172] L.M. Chounet et al., Phys. Reports C4(1972)199
- [173] D.R. Botterill et al., Phys. Rev. 171(1968)1402
- [174] J. Heintze et al., Phys. Lett. 60B(1976)302
- [175] K. Kleinknecht, Proc. Int. Conf. on High-Energy Physics, Munich 1988,
p. 98
- [176] see e.g. S.M. Bilenky in Neutrino Physics, ed. K. Winter, Cambridge
Univ. Press 1991, p.177

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