[a]

THE DISCOVERY OF WEAK NEUTRAL CURRENTS

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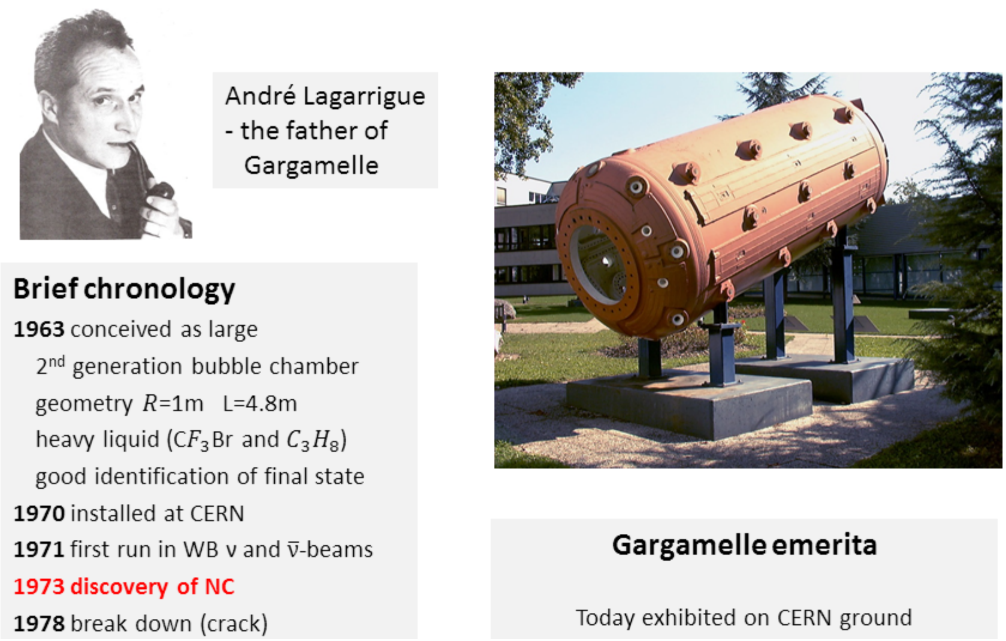
The order of events from end 1971 until spring 1974 is outlined. It starts with the situation when the collaborations Gargamelle and the HPW took up the challenge to search for weak neutral currents. The background to both experiments is discussed. The criticism Gargamelle had to face after the publication is described and the period of the following months with new experimental information which eventually confirmed the claim of Gargamelle.

1 Introduction

Voici Gargamelle !



The bubble chamber Gargamelle, after its rich life, can be admired on CERN ground. Its name will remain connected with the discovery of weak neural currents [1,2].

At the beginning of the 1960s the high energy neutrino beams at CERN and BNL opened the GeV regime for the study of weak interactions. The key notion was *high energy*, since it was clear

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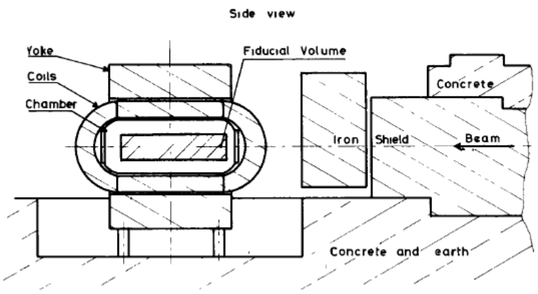
that the V-A theory, working very well in the sub-GeV regime, should reveal new phenomena at high energies. The low statistics of the first data and the large physics potential inspired André Lagarrigue to conceive at the Siena conference 1963 a next generation bubble chamber 5m long, 1m in diameter and filled with a heavy liquid holding the promise of deeper insight in the properties of weak interactions. When Leprince-Ringuet saw the drawing of the big chamber he gave it the name *Gargamelle*, an illustrous figure in Rabelais' work. Lagarrigue formed a large collaboration of 7 european laboratories: Aachen, Brussels, CERN, École Polytechnique, Milan, LAL Orsay, UC London. The physics program was discussed in a 2-day meeting at Milan in autumn 1968. The search for the *intermediate vector boson*, supposed to mediate weak interactions, was prominent on the list of topics to be investigated. The current prejudice was that its mass is on the order of a few GeV. It was therefore expected to be detectable either by direct production or at least through its propagator as a deviation from the linear rise of the total neutrino cross section. A hot topic attracting the attention came from the just discovered substructure of the proton at SLAC. With Gargamelle in the neutrino beam this new phenomenon could then be probed through the weak current as opposed to the electromagnetic current in proton-electron scattering at SLAC. New features may be expected to emerge due to parity violation and the electromagnetic charge of the weak charged current. Among the variety of other topics the question of weak neutral currents did not play any role, yet precisely this topic should make Gargamelle famous. The proposal was approved 1970. Data taking started in spring 1971.

On the other side of the Atlantic the new National Accelerator Laboraory NAL, subsquently called Fermi Laboratory, was preparing 1970 neutrino physics at the 100 GeV scale. One of the two approved experiments, namely E-1A, was proposed by the Harward-Pennsylvania-Wisconsin collaboration [3] (HPW) and built through 1972. Its aim was the study of neutrino interactions at highest energies, in particular to find the *intermediate vector boson* $W^{\pm}$. Neutrinos from an unseparated wideband beam interact in a 150 ton liquid scintillator calorimeter followed by a magnetic iron spectrometer to detect and measure outgoing muons (see Fig. 1). Neutral current interactions were initially not thought of.

2 The Search

Great discoveries have sometimes to wait until the right moment has come. This is true for the discovery of weak neutral currents. The theoretical progress [4,5,6] in the understanding of weak interactions during the 1960s was largely ignored by the experimental groups and got the deserved attention only 1971, when 't Hooft [7] and Veltman [8] came up with a proof of the renormalisability. The question of whether weak neutral currents, in addition to the known charged currents, existed or not, became then an urgent issue. At that moment two large detectors (see Fig. 1) were available to take up this historic chance : the heavy liquid bubble chamber Gargamelle at the CERN PS and the E-1A detector at the NAL PS.



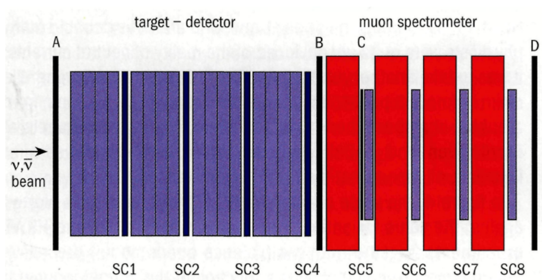


Figure 1 – Setup of the Gargamelle and E-1A experiments

Data taking at CERN started in Spring 1971. The data were distributed among and evaluated by the seven collaborating laboratories. In order to ensure equal quality the events observed in the fiducial volume of the bubble chamber (see Fig. 1) were classified in four categories as shown in Table 1.

Table 1: Scanning rules.

Class A.	Events with a muon candidate
Class B.	Events with identified hadrons
Class C.	Events with proton stars
Class D.	Events with isolated leptons only

The incoming neutrinos or antineutrinos hit the freon molecules of the chamber liquid, i.e. nucleons in the nuclei and electrons of the electron clouds. The ν_μ-beam generates $\nu_\mu + N \to \mu^- + anything$ and similarly the $\overline{\nu}_\mu$ beam $\overline{\nu}_\mu + N \to \mu^+ + anything$, i.e. the charged current processes known at that time. Such events are collected in class A. The final state muons usually leave the chamber and are observed as a curved smooth track running from the event vertex in the fiducial volume of the chamber until the end of the visible volume. This same topology occurs also, if instead an entering neutron interacts in the chamber emitting a charged hadron and leaving the chamber without visible interaction. Such neutrons arise naturally in upstream neutrino interactions and contribute an unavoidable background to the events in class A, as was well known from the previous neutrino experiments. For this reason the class B has been introduced, since these events are supposed to be induced by neutrons and therefore serve to determine the neutron background among the events in class A. The events in class C consist of only one or more protons. Charged current ν_μ or $\overline{\nu}_\mu$ interactions off electrons are forbidden. Thus the observation of a single electron is the signal of a new effect, such as a weak neutral current.

The analysis was in full progress, when the Gargamelle collaboration was approached at the end of 1971 by its theory friends and confronted with the request to search for the new type of weak force mediated by a neutral intermediate vector boson Z in analogy to the W. Events induced by a Z would, if they really existed, have the same topology as the events already collected in class B. This fortunate circumstance enabled the collaboration to embark on the search without any delay.

Scanning and measuring proceeded quickly and was completed by Spring 1973. In December 1972 an inspiring event was found in class D by the Aachen group in the antineutrino film, as shown in the left hand side of Fig. 2. The event [9] consists of an isolated uniquely identified

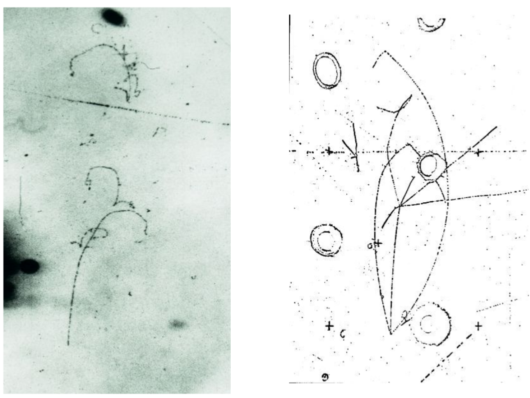


Figure 2 – Two events : leptonic and hadronic neutral current candidate

electron and, after careful background studies [10], was attributed to $\overline{\nu}_\mu + e^- \to \overline{\nu}_\mu + e^-$, i.e. the first candidate for a leptonic neutral current interaction. The confidence in this interpretation relied of the fact that the event occurred in the antineutrino film and, consequently, the charged current background from $\nu_e + N \rightarrow e^- + invisible\ \ hadrons$ is negligible. This event aroused an enormous excitement within the collaboration and fired the optimism towards a discovery.

On the right hand side of Fig. 2 is displayed a hadronic neutral current candidate. It is a clean 3-prong event of about 6 GeV. All particles in the final state are manifestly identifying themselves as hadrons.

The E-1A experiment [3] focussed initially on the energy dependence of the neutrino cross section and the search for the W. When the priority was changed 1972 to the search for weak neutral currents, it was essential to have both a muon trigger and an energy trigger. The signature of neutral current candidates consists in a sizeable energy deposition in the calorimeter and the absence of a muon in the muon spectrometer. A charged current interaction, where the final state muon is not detected, simulates a neutral current interaction. The first events without muon were observed in Spring 1973.

3 The March Meeting

When Lagarrigue opened the collaboration meeting in March 1973 at CERN, he had good reasons to be euphoric. He reported on the analysis of 83.000 pictures taken in the neutrino beam and 207.000 pictures taken in the antineutrino beam. To the great surprise the number of neutral current candidates (NC), i.e. events consisting of identified hadrons without muons or electrons in the final state, was large, on the order of 100 events. In addition, a sample of charged current events (CC) has been selected requiring the same criteria for the hadron state, but ignoring the muon, such that a direct comparison between NC and CC was possible. The ratio NC/CC was found to be of order 1. Furthermore, there was the unique and exciting candidate for the elastic neutral current interaction off an electron (see Fig. 2).

The expected shape of the event vertices along the chamber axis was anticipated to be

- exponentially falling at the beginning of the chamber for neutron induced events, since the interaction length of neutrons in the chamber liquid was calculated to be 70 cm
- flat for neutrino induced events
- flat, of course, for the CC events in the comparison sample, since they are for sure neutrino induced

Due to the large longitudinal extention of the chamber a genuine neutral current signal should then manifest itself by a nontrivial flat tail of events in the second part of the fiducial volume. These features are indeed emerging from the distributions in Fig. 3. It was tempting to conclude that a discovery was at hand, if two critical remarks had not damped the euphory. Although the above considerations were suggested by a simple Monte Carlo of the Orsay group, they relied on the tacit assumption that the neutrino flux enters just through the front window of the chamber. A look at the radial shape of the known flux distribution reveals, however, a nonnegligible extention well beyond the chamber body. The setup displayed in Fig. 1 shows that the chamber body is surrounded by the magnet coils and the yoke, i.e. heavy material. The neutrino flux penetrating these lateral parts generates a huge amount of neutrino interactions, which are largely unobservable. Due to the angular distribution of the emitted neutrons a certain fraction of these neutrons enter the visible part of the chamber and generate a flat vertex distribution just as genuine neutrino interaction are doing. The distinctive feature described above is put in question.

There was a second critical remark important in judging the size of the neutron background. It has not been taken into account that neutrons can make cascades, if they are energetic enough. This is relevant for the interactions outside the visible volume of the bubble chamber. The Fig. 4 sketches the setup in terms of neutron interaction lengths. The number of neutrino interactions

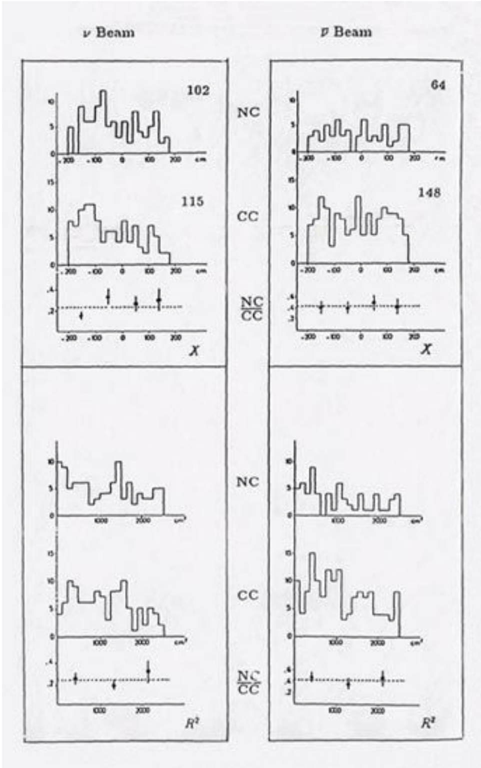


Figure 3 – Vertex distributions of NC and CC events in neutrino and anrineutrino beams

is roughly a constant per interaction length. The amount of neutrino interactions outside the chamber liquid is therefore by a huge factor larger compared to the number inside. The size

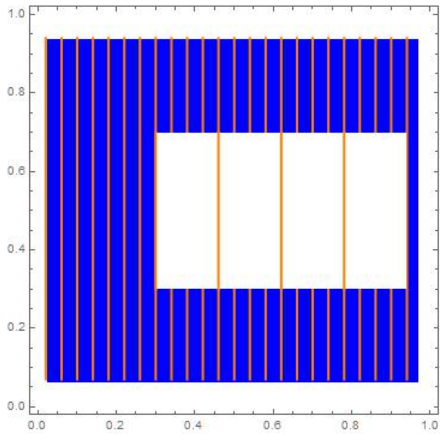


Figure 4 – The Gargamelle setup in slices of one interaction length

of the neutron background is proportional to the cascade length rather than to the smaller interaction length.

The net effect is that the background of neutrons may be considerably underestimated and much more dangerous than anticipated for the two reasons stated above, i.e. neutrons entering from the side and the cascade effect. Without a distinctive feature between signal and background the existence of a new effect can only be claimed, if the absolute number of background neutrons can be shown to be small compared to the number of signal events. Being fully aware of the competition with HPW the Gargamelle collaboration decided to dedicate a few months to elaborate on the implication of these critical remarks on the size of the neutron background.

4 The Neutron Background Calculation

The calculation of the neutron background requires four ingredients, as shown in Table 2. Given

Table 2: Ingredients for the neutron background calculation.

Matter distribution	complex setup, but known
Neutrino flux	$\Phi(E_\nu, R)$ measured versus E_ν and radially
Dynamics of hadron final state	obtained from ν-events
Evolution of hadrons in matter	need a cascade model

the complexity of the task the Monte Carlo method was appropriate to handle the four ingredients. A modular structure was chosen, which allowed to get preliminary results, while still improving and refining various aspects. This turned out to be a useful feature later on, when the impact on the size of the predicted background had to be examined for various deliberately chosen conditions.

The implementation of the first three topics was straightforward, though quite time-consuming. The last topic looked at first hopeless. Each hadron in the final state starts its own cascade depending on the kinematic conditions and leading to complex transport phenomena in the different parts of the setup. The hope for a timely solution was becoming real, when it was recognized, that an interacting final state meson would never be able to generate a secondary neutron depositing in an interaction more than 1 GeV, as required for neutral current candidates. Thus the cascade process restricts to nucleons, neutrons or protons, and becomes a linear transport problem. The cascade outside the bubble chamber is not observable and is transported by both neutrons and protons, with the requirement that in the last step it must be a neutron which enters the bubble chamber. It remained to establish the elasticity distribution which tells at each interaction point how much energy is deposited and how much energy is transported away. Furthermore the angular distribution of the emitted nucleon had to be determined. Both distributions have been obtained from published *pp*-data.

In conclusion, the neutron background [13] can be predicted absolutely. It has no free parameters and takes into account the full details of the experiment.

5 The Proof

A neutron induced interaction is observable inside the bubble chamber in two topologies (Fig. 5) :

- as the *end* of the cascade in the upstream shielding, called *B event* (background event)
- as the *beginning* of the cascade downstream inside the visible part of the chamber, called *AS event* (associated event).

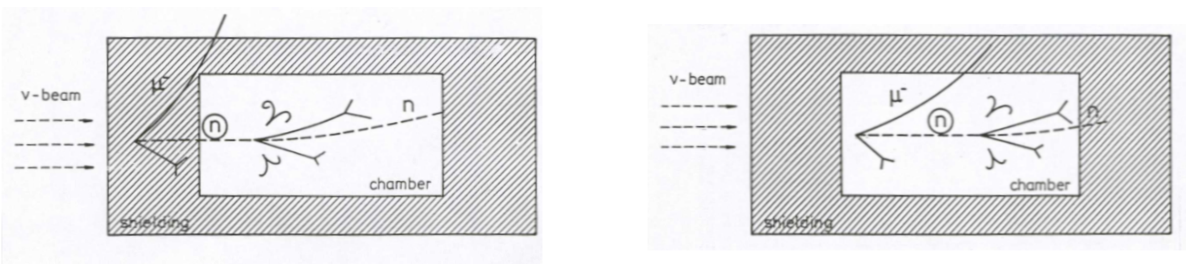


Figure 5 – Two topologies of a backgound event in the chamber

The prediction of the ratio B/AS is then mainly depending upon the properties of the cascade. At the beginning of July 1973 the background program was ready and as well the sample of AS events was completed. Consider now the

hypothesis : *all neutral current candidates are due to neutron background.*

In this worst possible case the experimental value of B/AS amounts to 102/15 for the neutrino film and 64/12 for the antineutrino film, since by assumption the number of B events is equal to the number of NC candidates. On the other hand the neutron background program predicts for the B/AS ratio 0.7±0.3 in eclatant contradiction to the observed ratio. Therefore, the hypothesis must be rejected and it must be concluded that the NC event sample is dominantly neutrino induced, while neutron induced events contribute only about 10%.

It is also possible to reconstruct from the vector sum of the hadron final state the flight direction of the incoming particle and to determine by the classical Bartlett method its mean free path using the measured flight and potential paths. Again the mean free path of the NC sample is similar to the neutrino induced CC comparison sample, while strongly different from the known mean free path of neutrons in the chamber liquid.

In the weeks until the end of July intense discussions followed, where the members of the collaboration had scrutinized all aspects of the background calculation. Particularly the treatment of the cascade was critically examined. Stretching all ingredients to its limits could not endanger the claim that neutrino induced events without charged lepton in the final state had been observed. Finally, when all members of the collaboration were satisfied the paper was submitted on July 25, 1973 to Physics Letters [11], followed later by a more detailed account [12]. The paper of the leptonic NC candidate [9] was already sent for publication at the beginning of July.

6 The BONN Conference

The discovery of weak neutral currents has been reported to the Electron-Photon Conference held at Bonn in August, 23-27, 1973. It has been for the first time that results on weak interactions were included. From that moment on the name of the conference changed to Lepton-Photon Conference.

As a last-minute contribution the HPW collaboration has submitted their analysis to the conference. It consisted of the data which were submitted to Phys.Rev.Letters in May 1973, but not yet accepted. The HPW data have been included in the Gargamelle talk [14] and found to be consistent with the Gargamelle result. Further evidence for the existence of weak neutral currents came from the 12 foot bubble chamber group at ANL with the observation of exclusive pion production [15]. An attempt has been made to interpret the data within the Glashow-Salam-Weinberg model. Rough consistency was found for a value of $\sin^2\theta_W \approx 0.3$.

In concluding the conference C.N.Yang has announced that weak neutral currents have been discovered.

7 The Hot Fall

The great satisfaction within the Gargamelle collaboration did not last untroubled. Physicists at CERN and abroad shed doubts on the background analysis, in particular on the treatment of the cascade. Some went as far as claiming that Gargamelle merely *rediscovered the neutron.* The opponents did not put forward a single argument, which had not been considered before publication. The members of the collaboration had no difficulty in rejecting every concrete argument, nevertheless there remained an emotional disbelief. This situation became worse, when rumours from HPW reached CERN that the effect had disappeared. What happened, was that the HPW collaboration had modified their detector by inserting a 13 inch iron plate at the end of the calorimeter and before the muon spectrometer. Their aim was to increase the muon angular acceptance and to obtain more and cleaner event samples of neutral current candidates. This goal was indeed achieved, but, unfortunately, it escaped to the collaboration that high energy hadrons were now punching through this far too thin *shielding* with the net effect that genuine NC candidates were misinterpreted as CC events. Thus the NC signal got lost. The collaboration decided to inform Lagarrigue in a letter (Fig. 6) dated November 13, 1973 about the disappearance of the NC signal. In principle, the findings of both HPW

Figure 6 – Letter announcing the absence of weak neutral currents

November 13, 1973

Professor A. Lagarrigue, Director
Linear Accelerator Laboratory
University of Paris - SUD
Centre D'Orsay
Batiment 200
91405 Orsay
France

Dear Professor Lagarrigue:

We write to inform you of the preliminary result of our recent experiment to search for neutrino interactions without final state muons. As you know, our apparatus was modified to provide a much larger detection efficiency for muons relative to the apparatus that was used in our earlier search for muonless events. We also improved our ability to locate accurately vertices of observed neutrino interactions, and lowered the threshold on the total energy of the hadrons in the final state.

From about one half of the data obtained in our recent run, we find the raw ratio $R_{raw} = 0.18 \pm 0.03$. We estimate the muon detection efficiency of the apparatus for the enriched antineutrino beam that was used in this experiment to be approximately 0.85. Taking into account small backgrounds produced by incident neutrons and by ν_e in the incident beam, the corrected ratio is $R_{corr} = 0.02 {}^{+0.05}_{-0.03}$, where the error includes an estimate of the uncertainty in the calculated detection efficiency. We are continuing to process the remainder of the data and to improve our understanding of the experiment.

We have written a paper intended for Physical Review Letters which will soon be submitted. A copy will, of course, be sent to you but for obvious reasons we wanted to convey our result informally to you before its publication.

With kindest regards

Yours sincerely,

D. Cline D Cline

A. K. Mann

D. D. Reeder

AKM/rs

C. Rubbia Carlo

and Gargamelle could coexist by assuming that weak neutral currents are energy dependent. However, the prevailing attitude was, that Gargamelle must be wrong. It is no wonder that the CERN Directorate got worried and was fearing another debacle following the one about the *split* A_2. After a privatissimum with representatives of the Gargamelle collaboration the members of the CERN directorate felt somewhat relieved.

8 The Proton Experiment

Despite all the doubts and the widespread disbelief the Gargamelle collaboration stood firm. Yet to overcome the continuing criticism a way out was found by performing a special experiment. To this end pulses of protons with fixed energy were shot into the bubble chamber Gargamelle. The proton induced interactions in the chamber liquid provide the explicit inspection into the behavior of cascades. The neutron background program was adapted to the particular conditions and the expected outcome of the proton induced interactions was predicted in advance, thus ensuring an unbiased check. Gargamelle was exposed to pulses of protons with 4, 7, 12, 19 GeV in two runs in November and December 1973. In Fig. 8 a many-step-cascade induced by a 7 GeV proton is displayed. By measuring the vertex positions of the first interaction and last

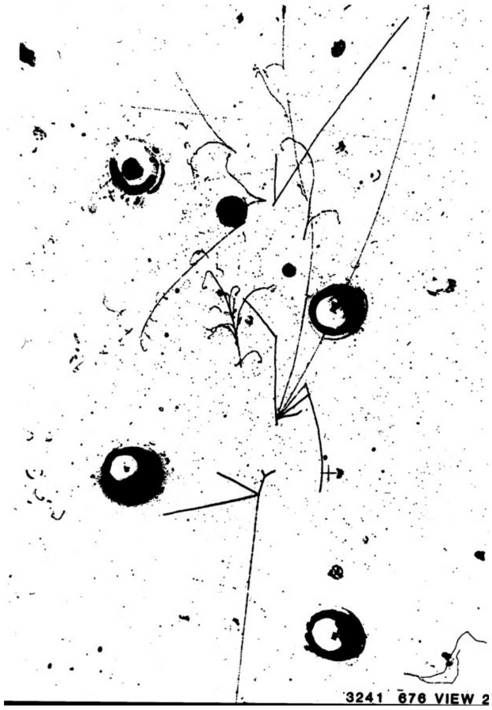


Figure 7 – A cascade induced by a 7 GeV proton

interaction of the cascade still satisfying the 1 GeV energy criterion, the apparent interaction length and the cascade length were obtained. The measurements are shown in Fig. 8 together with the predicted distributions shown as dashed lines. The analysis of the proton experiment

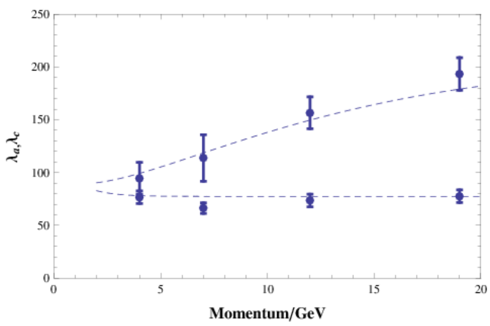


Figure 8 – Energy dependence of the apparent and cascade lengths; the dashed lines are the prediction by the neutron background program.

was completed at the beginning of 1974. The results have been reported to the APS Meeting at Washington [16] in April 1974.

In conclusion, good agreement is found between observation and prediction. This is the unambiguous confirmation that the treatment of the nucleon cascade in predicting the neutron background in the neutral current sample was realistic and quantitavely correct.

9 Consensus

In Spring 1974 ample evidence for the new effect was available. The status can be summarized as follows :

1. Gargamelle's claim that the observed events without charged lepton in the final state constitute a new effect, withstood all criticism. In the meantime the event sample has been doubled in agreement with the initial findings. The conclusion that the neutron background is at the level of 10 % relies on its absolute calculation. The critical part of the prediction, the treatment of the neutron cascade, is consolidated by a special experiment. The smallness of the background is furthermore confirmed by measuring the mean free path of the neutral current candidates.

2. Single pion production by the weak neutral current has been observed at ANL in the 12 foot bubble chamber filled with hydrogen and deuterium [15]. The two channels

$$\begin{aligned} \nu_\mu p &\rightarrow \nu_\mu n \pi^+ \\ \nu_\mu p &\rightarrow \nu_\mu p \pi^0 \end{aligned}$$

   have been studied in exposures of about 300.000 pictures and compared with the charged current reaction $\nu_\mu p \rightarrow \mu^- p \pi^+$. The neutron background was estimated using the 3-prong events of the process $np \rightarrow pn\pi^-$ and identified by a 1-constraint fit.

3. The CalTec-Fermilab group [17] has performed a search for neutrino and antineutrino induced events without muon in the final state in a narrowband neutrino beam. They applied the event length as a new technique for distinguishing neutral from charged current events. They obtained event samples of 998 and 646 in the neutrino resp. antineutrino runs.

4. The HPWF collaboration has finally understood that the insertion of the 30 inch iron plate caused the loss of genuine neutral current events as a result of punch through. In their revised analysis [18] they now also confirm the existence of neutrino induced events without final state muons. Table 9 lists the cronology of the events.

Table 3: Publication cronology of the HPW collaboration.

July 17, 1973	Rubbia informs Lagarrigue on 100 unique NC events
August 3, 1973	Paper submitted to PRL
Bonn conference	Last minute contribution included in Gargamelle presentation
September 14, 1973	Slightly revised version resubmitted Collaboration decides afterwards to postpone publication and to wait for more data with modified detector
November 13, 1973	HPW informs Lagarrigue about absence of NC
Februar 25, 1974	Revised paper with existence of NC resubmitted to PRL
April 8, 1974	Paper appeared in PRL 32 (1974) 800

10 Impact

All major laboratories have set up a longterm research program to explore the new force. The discovery of weak neutral currents paved the way towards the electroweak theory [19]. The gauge principle plays an essential role : the U(1) of QED is extended to the gauge group SU(2)x(U(1), where both electromagnetic and weak interactions are treated on the same footing. In retrospect, the old V-A theory appears as the low energy form of the embracing electroweak theory. Likewise are electroweak processes precisely predicted by photon exchange alone as long as the relevant scale is small compared to the weak boson masses, i.e. QED remains a consistent theory by itself. The electroweak theory consists of three sectors, namely the flavour sector, the gauge boson sector and Higgs sector, each with free parameters to be determined by experiment. This goal has been achieved by forming bigger and bigger collaborations, by constructing sophisticated omnipurpose detectors, by building new accelerators and colliders and by steadily increasing computing power.

A few milestones along the electroweak way shall be highlighted :

1. The understanding of the gravitational collapse phenomena, which were sofar based on processes mediated by the W, got with the Z, coupling to all three lepton pairs, a new and efficient access [20].

2. The masses of the gauge bosons can be predicted within the Glashow-Salam-Weinberg model. Using the measured value for $\sin^2\theta$ one obtained 1976, three years after the discovery, for the mass of the W :

$$M_W = \frac{\pi\alpha/\sqrt{2}G}{\sin\theta} \approx \frac{37.3\,\mathrm{GeV}}{\sqrt{0.3}} \approx 70\,\mathrm{GeV}$$

   This high value explains a posteriori, why the accelerator neutrino experiments were searching in vain for the presence of a propagator effect through a deviation from the linear rise of the total neutrino cross section. Incidentally, one had to wait another 20 years until HERA with its much larger center of mass energy came into operation to manifest the W-propagator owing. Cline, Rubbia and Mc Intyre proposed 1976 to build a $p\overline{p}$ collider in order to produce directly the weak bosons W and Z. This project was realised at CERN and led to their discovery [21].

3. High precision phase of neutrino physics. The measurements of the ratio NC/CC in neutrino experiments were initially compared with the theory at leading order. The resulting value of $\sin^2\theta$ is shifted by 0.010, when instead the theory is applied at first order. This was the incentive to improve the experimental precision to $\pm$ 0.005. The two collaborations CDHS and CHARM have indeed achieved this excellent precision and thus contributed a test of the gauge character.

4. With the experimental knowledge of the Z mass the e^+e^- colliders SLC and LEP were built to run at and around the resonance allowing tests with unprecedented precision. Runs at still higher center of mass energy gave access to W production with a test of the triple-boson vertex ZWW.

5. Along with the experimental study of radiative processes it was possible to predict the mass of the top quark, which was subsequently observed at the Tevatron confirming the surprisingly large mass value.

6. The discovery of the Higgs boson governing spontaneous symmetry breaking completed and crowned the test of the electroweak theory.

In summary, it is an outstanding success to have four decades after the discovery of weak neutral currents a full-fledged theory describing all electroweak phenomena.

11 A personal note

The search for weak neutral currents and their discovery have nothing lost of the fascination even after 45 years. The exciting time to work in the pioneering atmosphere of the Gargamelle collaboration is fresh in my memory. It was a privilege for me to have been a member of Gargamelle and to have felt the responsibility in a discovery situation.

Acknowledgements

It is a pleasure to thank Daniel Vignaud and Michel Cribier for the invitation to this most interesting conference and the occasion to meet many colleagues from old times. I like to thank Peter Zerwas for enlightening discussions on many aspects of weak interactions.

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