The Discovery of Weak Neutral Currents

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The beginning of high energy neutrino physics at CERN is outlined followed by the presentation of the discovery of weak neutral currents in the bubble chamber Gargamelle.

1. Preface

Neutrino physics has played a prominent role in the history of CERN. The very first large project at the Proton Synchrotron starting in 1960 was a neutrino experiment aimed at solving one of the urgent questions in the understanding of weak interactions. It was the beginning of a long range program. Its highlight was the discovery of weak neutral currents in the bubble chamber Gargamelle. Four decades passed since then and the huge impact of the discovery both for CERN and worldwide stands out clearly.

This article begins with a glance at the first neutrino experiment at CERN and focusses then on the discovery of weak neutral currents in the Gargamelle experiment. For personal testimonies of the beginning neutrino physics at CERN see Refs. 1 and 2. The discovery of weak neutral currents has been the subject of dedicated conferences[3–5] and several reviews, e.g. Refs. 6–9.

2. The Beginning of High Energy Neutrino Physics at CERN

2.1. *Status of weak interactions at the end of the 1950s*

It was beyond imagination, when Pauli invented in 1930 the neutrino in a stroke of genius, that once it would become the tool par excellence to investigate the leptonic sector of weak interactions. Right after sending the famous letter to his *radioactive friends in Tübingen*, Pauli told his astronomer friend Walter Baade:[10] "*I have today done something terrible which no theoretician ever should do and proposed something which never will be possible to be verified experimentally.*" Shortly afterwards, Fermi formulated his theory of β-decay[11] on the basis of Pauli's neutrino hypothesis and the recently discovered neutron. Bethe and Peierls[12] calculated in the following year the cross-section for a neutrino induced process and found it hopelessly small. Only much later, in 1946, it occurred to Pontecorvo,[14] that with the advent of powerful nuclear plants and their high antineutrino fluxes there may be a chance. Indeed, Cowan and Reines succeeded in detecting the first neutrino induced reactions at the Savannah River reactor. They observed the inverse β-decay: $\overline{\nu}_e + p \rightarrow e^+ + n$. So, 26 years after the formulation of the neutrino hypothesis, June 14, 1956, Cowan and Reines could send a telegram to Pauli saying: "*We are delighted to tell you that we have definitely found neutrinos through observing inverse β-decay.*" Pauli prompted: "*Everything comes to him who knows how to wait.*"

The Dirac equation for fermions written in terms of 4-spinors can conveniently be written as a set of coupled equations with Weyl 2-spinors. These equations have the interesting property to decouple for massless fermions, such as it was assumed for the neutrino. The Lorentz structure in the original Fermi theory of beta decay was not specified, it could involve scalar, pseudoscalar, vector, axialvector or tensor contributions. The experimental investigation of nuclear and particle decays have shown that the interaction is of the type V, A. The demonstration in 1957 that parity is maximally violated in weak interactions, has prompted the 2-component theory of the neutrino and the formulation of the $V - A$ theory of weak interactions.

This inspired immediately the idea of a weak intermediate vector boson as the analog to the photon in electromagnetic interactions. The processes at that time, mainly decays, involved only small momentum transfers and thus appeared as effective 4-fermion interactions. This raised interest in experiments at much larger momentum transfer soon accessible at the planned accelerators of CERN, Dubna and BNL for the investigation of the existence of an intermediate vector boson and the properties of weak interactions in general.

Another fundamental question arose in the study of muon decays: $\mu^+ \rightarrow e^+ + \nu + \tilde{\nu}$ and $\mu \rightarrow e + \gamma$. It was known that the leptonic muon decay is a 3-body decay consisting of an electron and two light nonidentical neutrals. They could be the known neutrino and its antiparticle. However, there was no compelling reason for being particle and antiparticle, there could also exist two distinct neutrino species. The same question appeared also in the attempt to understand the absence of the decay $\mu \rightarrow e + \gamma$. If the decay is assumed to involve an intermediate vector boson, then it should not be suppressed. Feinberg[16] argued that the decay could nevertheless be suppressed, if the neutrinos associated with the two vertices are different. Pontecorvo devoted in Refs. 17 and 18 a thorough discussion of the 2-neutrino question and proposed ways to tackle it experimentally.

The idea of high energy neutrino beams derived from pion decays for answering these outstanding questions were considered by Pontecorvo,[19, 20] Markov[21] with his young collaborators Zheleznykh and Fakirov and by Schwartz[22] and T. D. Lee.[23] Pontecorvo recalls in Ref. 24 how he came to propose a neutrino beam at high energy from meson factories and from very high energy accelerators.

2.2. *The first neutrino experiment at CERN*

In 1960 the time has come to realise the idea of high energy neutrino beams at the new accelerators of CERN and BNL. The first operation at the CERN proton synchrotron was at the end of 1959, the Brookhaven AGS started a year later in autumn 1960. Bernardini[25] was at that decisive time director of research at CERN and recognised the potential of neutrino experiments to open a new and promising field of research for exploring the properties of weak interactions in a hitherto unprecedented energy regime with particular emphasis on solving the two burning questions, namely whether there exist two neutrinos and whether there exists an intermediate vector boson. Bernardini[26] reported the program of neutrino experiments and their feasibility at CERN to the 1960 Rochester conference.[a] Two weeks after his return to CERN appeared the proposal by Steinberger, Krienen and Salmeron[27] for an *experiment at CERN to detect neutrino induced reactions.* In a recent letter Steinberger[28] recalls: "*I am personally indebted to Pontecorvo for proposing, in 1959, to check experimentally if the neutrinos associated with muons in pion and kaon decay are the same, or not, as those in β decay, and that the higher energy accelerators, then under construction at Brookhaven and CERN, would permit neutrino beams of energy high enough to allow such an experiment (Pontecorvo 1959) — the experiment for which M Schwartz, L Lederman and I later shared the Nobel prize (Danby et al. 1962). Independently, Schwartz had proposed that neutrino beams would permit the study of weak interactions at higher energy, but he did not consider the particular question of the possible inequality of the two neutrinos, proposed by Pontecorvo (Schwartz 1960).*" The three authors studied the feasibility of a neutrino experiment at the CERN PS using a heavy liquid bubble chamber as detector. Basic questions addressed were:

- *Neutrino source*
  The protons from the PS strike a thin target in one of the straight sections. The pions produced at an angle of 6 degrees generate by their decay in flight the neutrino beam. The alternative would have been to postpone the experiment by about one year, until an external proton beam would be available. It has been argued that there is no compelling reason against a setup with an internal target.
- *Neutrino flux*
  The evaluation of the neutrino flux involves the initial pion flux and the pion decay kinematics. For the estimate of the actual number of events in the bubble chamber various efficiency factors had to be taken into account and, of course, the theoretical cross section of the process to be measured. A detailed consideration was devoted to the determination of the pion trajectories in the presence of the fringing field of the next magnet.

[a] He acknowledged Pontecorvo and Schwartz for the idea of this kind of experiment and added in the list of references and notes that also Markov and Fakirov had such ideas.

- *Size of the shielding*
  All hadrons and charged leptons travelling in the direction of the neutrinos have to be strongly absorbed, otherwise the scanning of the pictures and the interpretation of the events will be difficult. Furthermore, one has to worry about background from cosmic rays and neutrons. The requirements for the size of the shielding were considerable: 650 tons of iron and 4000 tons of heavy concrete have been estimated adequate.
- *Event rate and aim*
  The estimated rate was 1 event per day per ton of sensitive detecting material. A run of 2 to 3 weeks would be sufficient to settle the question of whether or not there are two types of neutrinos.

The authors concluded their proposal with the recommendation that CERN should make the effort to realise the experiment.

Bernardini presented the status of the neutrino program to the Scientific Policy Committee[29] in November 1960. The setting up of an experiment of this size was a real challenge for the young laboratory, since it required the coordination of several teams. The original layout was later on modified and finally three detectors came into operation, the Ecole Polytechnique bubble chamber, a cloud chamber complemented with electronic devices and the newly built NPA bubble chamber (the Ramm 1.2 m chamber). The next status report on the neutrino experiment to the 19th SPC in April 1961 from an engineering run was quite encouraging. However, three months later Bernardini had to announce at the 20th SPC meeting:[30] *"It is probably well known that the initial programme of experiments, with which at CERN we intended to open the field of the high-energy neutrino physics, is going through a crisis."* In fact, Guy von Dardel demonstrated that the flux was overestimated by an order of magnitude and thus no neutrino candidate could be expected. The failure was attributed to limitations in the beam optics at the internal target and to the simplified decay kinematics of the pions. Immediate remedies to increase the flux were discussed. Although solutions to increase the flux by one or two orders of magnitude were at hand, their realization on short terms was impossible. So, the race with the BNL group was lost. They[31] made the discovery of two neutrinos in 1962.

Even though this first experiment did not bring the expected success, it was nevertheless the beginning of high energy neutrino physics at CERN. In a second attempt the weaknesses have been overcome. An important achievement on the machine side was the fast extraction of the proton beam. The external proton beam was now hitting a thin and long target. The produced secondary pions and kaons were focussed efficiently by Van der Meer's newly conceived magnetic horn. The neutrino flux increased by more than two orders of magnitude. The shielding was improved and the CERN NPA heavy liquid bubble chamber (the Ramm chamber) was operated together with the spark chamber array.[32] Results were ready for the

Siena 1963 Conference.[33] Further runs with the Ramm chamber followed in 1964 with freon filling and 1967 with propane filling.

The initiative of Bernardini was the beginning of a long term program, which eventually brought about a fundamental result with the discovery of weak neutral currents.

2.3. *Early searches for weak neutral currents*

At the end of the 1950s weak processes were described as the interaction of two weak *charged* currents. This stimulated theoreticians quickly to think about a possible neutral current and a neutral intermediate field. Feynman and Gell-Mann merely noted in their famous publication:[34] "*We deliberately ignore the possibility of a neutral current, containing terms like* $\overline{e}e$, $\overline{\mu}e$, *etc. and possibly coupled to a neutral intermediate field. No weak coupling is known that requires the existence of such an interaction.*" Others speculated about implications of weak neutral currents, see for instance Refs. 35–37.

The successful description of all known low energy weak processes within the $V - A$ theory called the attention to the behaviour at higher energies. Lee and Yang[23] published in 1961 a catalog of fundamental questions to be addressed in the upcoming neutrino experiments. Among them was also the search for weak neutral currents. The experimental situation was however rather discouraging. The presence of weak neutral currents was first checked by examining the decay rates of elementary particles. Decays without change of the electric charge Q and strangeness S, i.e. $\Delta Q = 0$ and $\Delta S = 0$, were not useful, because they were dominated by electromagnetic interactions, therefore decays obeying $\Delta Q = 0$ and $\Delta S \neq 0$ were considered. However, both leptonic and hadronic kaon decays turned out to be dismayingly small. A new way of searching for weak neutral currents became possible in the CERN neutrino experiment 1963. The bubble chamber group has searched for the elastic process $\nu p \to \nu p$, i.e. a process with $\Delta Q = 0$ and $\Delta S = 0$. It turned out that neutron interactions represented a dangerous background, thus only an upper limit was obtained. Figure 1 shows Bernardini in the CERN auditorium with the upper limit of 5% (point 3 on the right black board) relative to the quasielastic process $\nu + n \to \mu + p$. A later revision[39] yielded 12±6%. The spark chamber group could not look for weak neutral currents, because they were running without the appropriate trigger. However, both groups searched for the existence of the intermediate vector boson. There was no sign of a resonance nor of an effect in the energy dependence of the total neutrino nucleon cross section. It had to be concluded, that the W, if it exists, must be heavier than a few GeV. A dedicated search[38] for weak neutral currents with the data of the NPA 1.2 m bubble chamber remained inconclusive because of the neutron background.

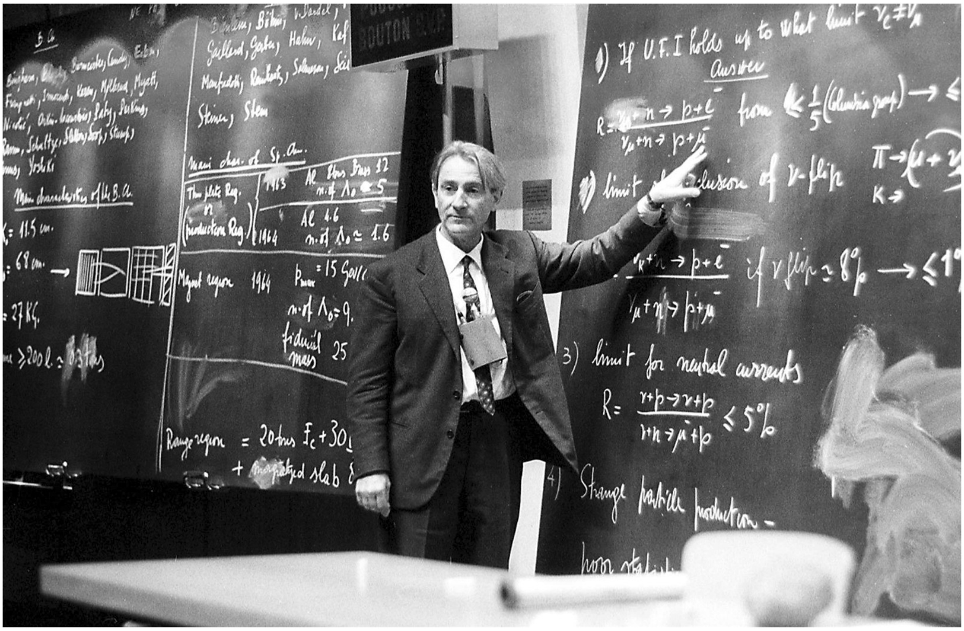

Fig. 1. Bernardini reporting in the CERN auditorium results from the Siena Conference 1963. © 1964 CERN.

3. The Discovery of Weak Neutral Currents

3.1. *The bubble chamber Gargamelle*

The results presented at the Siena conference demonstrated a great potential for future investigations of weak interactions. With the experience gained in the first neutrino experiment, Lagarrigue — like others — noted that a next generation experiment should be based on much larger statistics. His dream was to build a bubble chamber satisfying the requirements:

- *An order of magnitude more events*:
  need large target mass and intense flux (booster, focussing).
- *Good identification of muons and electrons*:
  must distinguish muons from charged pions requiring long path lengths in the chamber.
- *Detailed knowledge about final state*:
  must identify hadrons, neutral pions through their decay in two gammas (short conversion length), kaons through their decay, neutrons through interactions inside the chamber, charged hadrons through a visible interaction.

The result was a cylindrical bubble chamber 5 m in length and 1 m in diameter filled with a heavy liquid. When Leprince-Ringuet saw the giant chamber he called it after

Fig. 2. André Lagarrigue, the father of Gargamelle.

Rabelais *Gargamelle*. Figure 2 shows André Lagarrigue, the father of Gargamelle; he became professor at the university of Orsay in 1964 and director of LAL Orsay in 1969. He formed a European collaboration consisting of seven laboratories: III.Phys.Institut RWTH Aachen, ULB Bruxelles, CERN, Ecole Polytechnique Paris, Istituto di Fisica dell'Università di Milano, LAL Orsay and University College London. They met in 1968 for a two-day meeting at Milan to discuss the physics program. Although the search for the W, the carrier of weak interactions, remained at high priority, the discovery of the substructure of the proton by SLAC attracted the attention. Would the weak current in the neutrino experiment reveal the partonic structure of the proton as does the electromagnetic current in the *ep* experiment? New and additional information should then come from the fact that in a neutrino and antineutrino exposure probes with different charges are involved. Today the Gargamelle experiment is famous for the discovery of weak neutral currents, but while preparing the physics program this topic was not even discussed and ranged in the proposal[40] submitted in 1970 at low priority.

Figure 3 shows the chamber body inserted in the coils. One notices already here the huge amount of heavy material around the chamber body. The exposures to the improved neutrino and antineutrino wide band beams started in 1971. The films were shared among the seven laboratories. Strict scanning and measuring rules ensured the same standards in all laboratories. Based on the experience of the previous neutrino experiments with the Ramm chamber the events were classified in four categories:

(A) Events with a muon candidate
(B) Multi-prong events without muon candidate
(C) Proton stars
(D) Single electron or positron or gamma

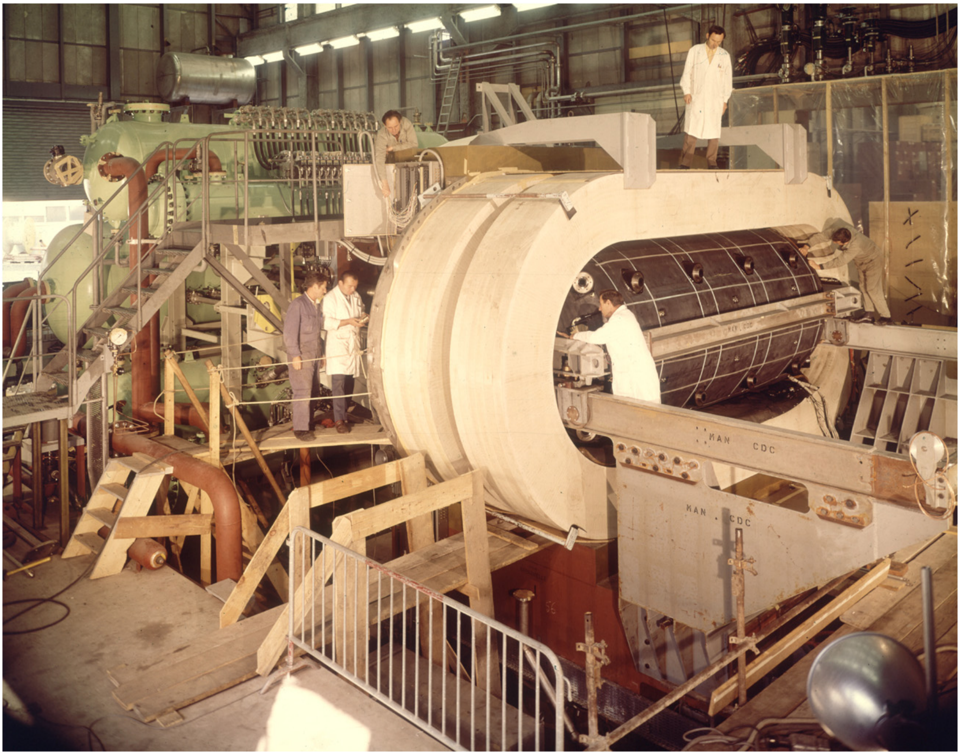

Fig. 3. The body of Gargamelle installed inside the magnetic coils.

At that time, a neutrino nucleon interaction was supposed to proceed as $\nu_\mu N \to \mu^- + X$ with X being a hadron system and was registered as event of type A. Neutrino induced events are characterised as multi-prong events with muon *candidate* defined phenomenologically as negatively charged noninteracting particle. Since muons are not explicitly identified, any charged particle with the appropriate charge will simulate a muon as long as it does not show a visible interaction. Therefore, the event sample A is unavoidably contaminated and must be corrected. The dominant background source are neutron induced events in the chamber. These neutrons are generated by neutrino interactions in the upstream heavy material. They produce interactions in the chamber, called *neutron stars*, and contribute to the class B, if *all* final state charged particles are identified as hadrons, whereas they contribute to class A, if one of the charged pions with the right charge does not interact in the visible part of the chamber. This contamination can be readily evaluated from the observed neutron stars in class B.

3.2. *The challenge*

The data analysis for investigating the parton structure of the nucleon was well in progress, when the theory friends of Gargamelle, in particular Jacques Prentki and Mary-Kay Gaillard, pointed out to the collaboration that a breakthrough in the theory of weak interactions had been achieved: the Glashow–Salam–Weinberg model encompassing both electromagnetic and weak phenomena in a local gauge theory. The immediate excitement arose from the fact that the model is renormalisable and that it predicted weak neutral currents, i.e. the process $\nu_\mu N \rightarrow \nu_\mu + X$, in addition to the well known charged current process $\nu_\mu N \rightarrow \mu^- + X$. If so, one should observe in Gargamelle neutrino induced events without a charged lepton in the final state. Although the collaboration was not prepared for such a search, it took up the challenge without losing time in view of the highly relevant topic. This was possible, because neutral current induced events, if they really existed, should already be present among the events in class B and just waiting to be identified. It was, however, clear from the outset, that the neutron background would be *the* problem.

A dedicated search for neutral current candidates was started. In order to reduce the background from neutrons a strong energy cut of 1 GeV was imposed on the hadronic final state. For future comparison a reference sample was formed from charged current events, where the hadron system respects the same criteria as for neutral current candidates. While the work was going on an exciting event in the antineutrino film was found at Aachen in December 1972. It consisted of a single completely isolated electron and was interpreted as a *leptonic neutral current* candidate $\overline{\nu}_\mu e \rightarrow \overline{\nu}_\mu e$, since all conventional interpretations could be safely excluded (see Ref. 41). This extremely clean event became later on famous and served as textbook example. No such event was found in the neutrino film. The interpretion within the Glashow–Salam–Weinberg model provided the very first constraint on the weak mixing angle.

3.3. *Status in March 1973*

Within less than one year a sizeable sample of hadronic neutral current candidates has been obtained. Lagarrigue was chairing the collaboration meeting in March 1973 at CERN. The status of the analysis is summarised in Table 1 and Fig. 4.

Figure 5 shows a neutral current candidate. There is evidently no lepton in the final state. Following track by track one notices a strong interaction and thus verifies its nature as hadron.

There were good reasons to be euphoric. In fact, three arguments seemed to hint at a new effect:

- *The distributions of the neutral current candidates look neutrino-like.*
  Their shapes are compared to the reference sample of neutrino induced CC events with the same properties as the NC candidates ignoring the muon.
- *The ratio of neutral current candidates over charged current events.*
  It is not small and it is flat both along the beam direction (X) and radially (R).

Table 1 The neutral current (NC) and charged current (CC) event samples in the ν and $\overline{\nu}$ films.

Event Type	ν-exposure	$\overline{\nu}$-exposure
# NC	102	64
# CC	428	148

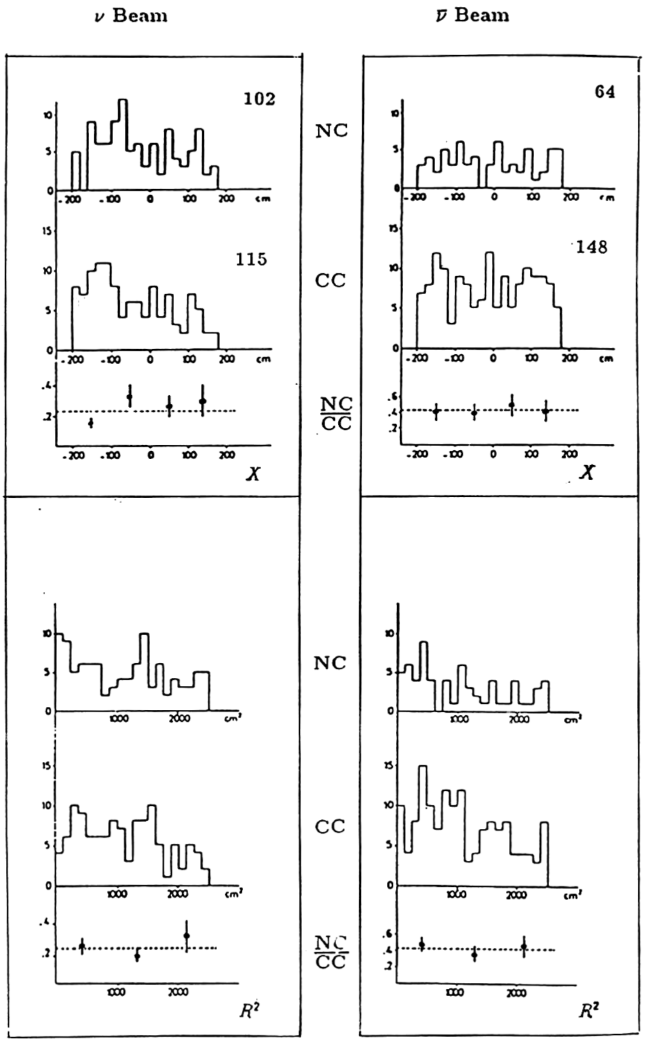

Fig. 4. Various distributions[43] of the neutral current (NC) and charged current (CC) samples; R denotes the radial and X the longitudinal position.

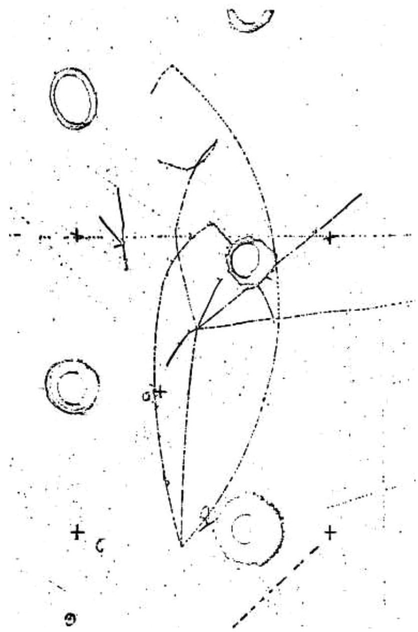

Fig. 5. Neutral current candidate.

- *The neutral current candidates do not look neutron-like.*
Otherwise the entering neutrons would produce a fall off in the first half of the chamber due to their interaction length being small compared to the chamber dimensions. This was corroborated by a Monte Carlo calculation of the Orsay group assuming simply a source of neutrons at the entrance window of the chamber.

The euphory was damped by two counter-arguments:

- *The neutrino flux has a broad radial distribution.*
The neutrons originating from upstream central neutrino interactions generate indeed a fall-off in the fiducial volume of the chamber, but a substantial fraction of the neutrino flux extends radially way beyond the fiducial volume and produces neutron sources distributed all along the nonvisible part of the chamber and further out to the coils. The net effect is that neutrons enter also laterally and thus generate a flat distribution along the chamber just as genuine neutrino-induced events do. The potential danger is obvious, since the outside material acting as source is a multiple of that contributing at the front (see Fig. 6).
- *Energetic neutrons in the iron shielding propagate in cascades.*
Neutrons entering the chamber and depositing there more than 1 GeV may be the result of a hadron cascade induced by the original neutrino interaction in the shielding. This means that the neutron background is not proportional

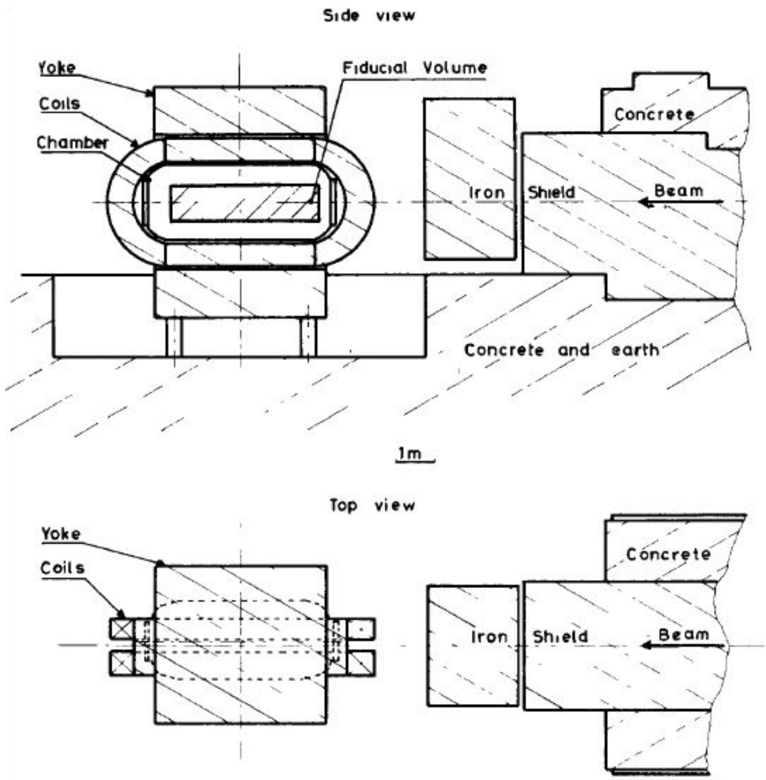

Fig. 6. The experimental setup is sketched in side and top views. The neutrino beam enters from the right through the shielding into the bubble chamber Gargamelle which is located inside the magnetic coils and the yoke. The fiducial volume inside the chamber body is also indicated.

to the interaction length, but rather to the cascade length which is bigger and energy dependent.

At the end of the hot meeting, it was clear that a quantitative estimate of the neutron background[b] was indispensable. A new effect can only be claimed, once it is unambiguously demonstrated that the contributing neutron background is small compared to the number of observed neutral current candidates.

3.4. *The neutron background*

Figure 6 displays the side and top views of the experimental setup. The neutrino beam passing the iron shielding from right to left enters the chamber, which is located inside huge copper coils. The chamber is filled with heavy freon of 1.5 g/cm^3. The cylindrical fiducial volume 0.5 m in radius and 4 m long is indicated in the

[b]Other background sources were studied, but found to be of no relevance.

upper view of Fig. 6. The target mass with about 5 tons is very small compared to the surrounding heavy material. The neutrons originate from upstream neutrino interactions. Their sources are therefore located according to the neutrino flux distribution. The neutrino flux has been determined experimentally by measuring the muon flux in the shielding and exploiting the constraint of the known meson flux and decay kinematics. The energy and angular distributions of the produced neutrons has been obtained from the observed neutrino events themselves.

Thus, the spatial and kinematic properties of the neutron source distribution could be safely established. The crucial aspect of calculating the neutron interactions simulating neutral current candidates in the chamber volume consisted in the treatment of hadron propagation in matter. The final state hadrons of an upstream neutrino interaction usually generate a shower in the shielding implying an increase in multiplicity. It has to be decided which of the particles leaving the shielding and entering the chamber would be able to simulate a neutral current candidate. It looked almost hopeless to come up in a short time with a reliable prediction, until it was realised[42] that only the nucleon component of the shower is relevant, since the mesons are unable to generate fast neutrons. Furthermore, it was recognised that the nucleon cascade is linear. So, the task was reduced to determine the elasticity distribution of fast nucleons in matter. This could be achieved from published nucleon–nucleon interactions. In conclusion, the prediction of the neutron background was free of unknown parameters.

A neutron interaction in the chamber can occur in two topologies, as illustrated in Fig. 7, depending on whether the neutron's origin is visible or not. The two event topologies are called *associated event* and denoted as AS, resp. *nonassociated, i.e. background event* and denoted as B. The interaction length of a neutron in the chamber liquid is about 80 cm, therefore a sizeable sample of AS events could be collected thanks to the large longitudinal extension of Gargamelle, namely 15 events in the neutrino and 12 in the antineutrino film. The observed numbers of AS and B events imply a constraint about the properties of the nucleon cascade, since the B-events represent the *end* of a nucleon cascade, while the AS represent the *beginning* of a cascade. At the beginning of July 1973 the background program was ready. First, the hypothesis *all neutral current candidates are background* was examined. This is the worst possible assumption. Then the ratio B/AS is for the neutrino film 102/15. The background program predicted for the ratio 1 ± 0.3 in manifest disagreement with the measured ratio. The data of the antineutrino film yielded the same conclusion. The hypothesis had to be rejected and the observed neutral current candidates are definitely *not all neutron background*. On the contrary, the neutron background accounts only for a small part. The next step was to evaluate the background using the angular and energy distributions appropriate for neutrons emitted in neutrino interactions. The result was $B/AS = 0.7 \pm 0.3$. The absolute number of neutron background events among the 102 neutral current candidates could then be predicted using the calculated ratio

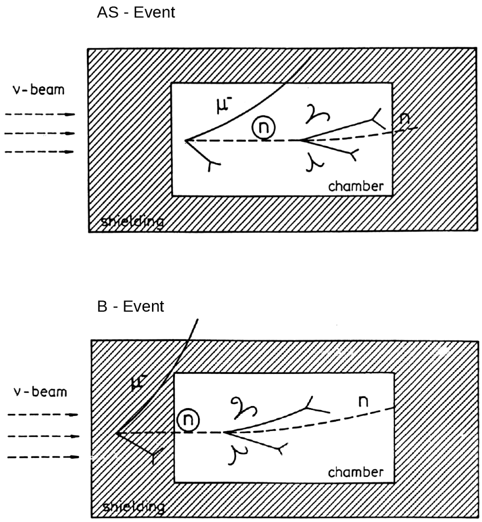

Fig. 7. Sketch of the tow topologies of a neutron interaction in the chamber.

B/*AS* and the observed number of *AS* events and yielded 10 for the neutrino data and similarly for the antineutrino data, thus a genuine new effect could be claimed.

This conclusion was intensively discussed within the collaboration. All ingredients of the background calculation were critically scrutinised. The modular structure of the program allowed for an immediate answer to the consequences of the proposed *ad hoc* modifications, particularly regarding the treatment of the cascade. At the end of July 1973 the collaboration was convinced that the observed *events without final state charged lepton* constitute a genuine new effect and sent the paper for publication to *Physics Letters*.[43] The single electron event[41] had already been sent off a few weeks earlier.

3.5. *The hot autumn*

A month later the discovery has been reported to the Electron–Photon Conference at Bonn. As a last-minute contribution also the Harvard–Pennsylvania–Wisconsin (HPW) collaboration contributed their observation. In a parallel session the new results were intensely debated. In his final talk C. N. Yang announced the discovery of weak neutral currents as the highlight of the conference.

Nevertheless some prominent physicists questioned the validity of the background calculation arguing that its underestimation, particular with regard to an optimistic treatment of the nucleon cascade, reduces the claim to nothing. Although Gargamelle's replies were safe and sound, the disbelief was strong and further increased, when the rumour got spread around that the HPW collaboration did not reproduce the effect in their modified setup. Given the implications of a failure the CERN management decided to perform an *experimentum crucis* to prove or disprove the validity of the neutron background calculation.

3.6. *The proton experiment*

Single proton pulses of fixed momentum (4, 7, 12 and 19 GeV) were extracted from the Proton Synchrotron and were sent to Gargamelle. Two runs were allocated, one at the end of November and another one mid-December 1973. The incoming protons initiate cascades just as do neutrons. The properties of these cascades could now be observed and investigated. An example of a cascade induced by a 7 GeV proton is shown in Fig. 8. For the application of the neutron cascade program only the initial condition had to be set to a proton with given momentum. Thus it was ensured that the crucial aspects of the program are really tested. Several critical questions to be answered were set up beforehand and the background program had to anticipate the expectations.

The answer to the two most important questions, namely the measurement of the apparent interaction length and of the cascade length, is shown in Fig. 9. The prediction of the apparent interactions depends upon the use of the relevant cross section, which is not just the total cross-section. A neutron is identified by a visible

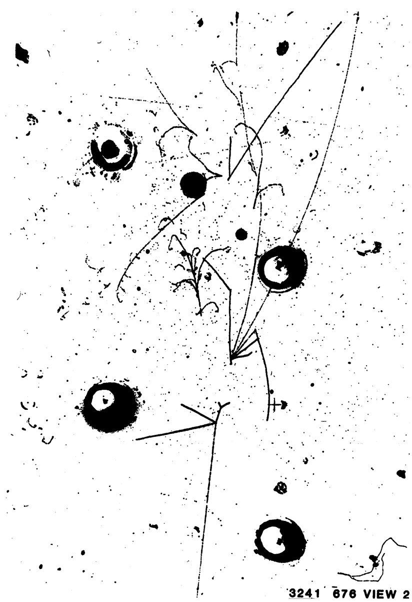

Fig. 8. Example of a multistep cascade initiated by a 7 GeV proton entering from below in the Gargamelle chamber. After the first interaction a charge exchange occurs and the cascade is continued by a fast secondary neutron, which in turn interacts, emits a fast proton interacting again and generating a π^0 and a neutron which interacts further downstream near the end of the visible volume.

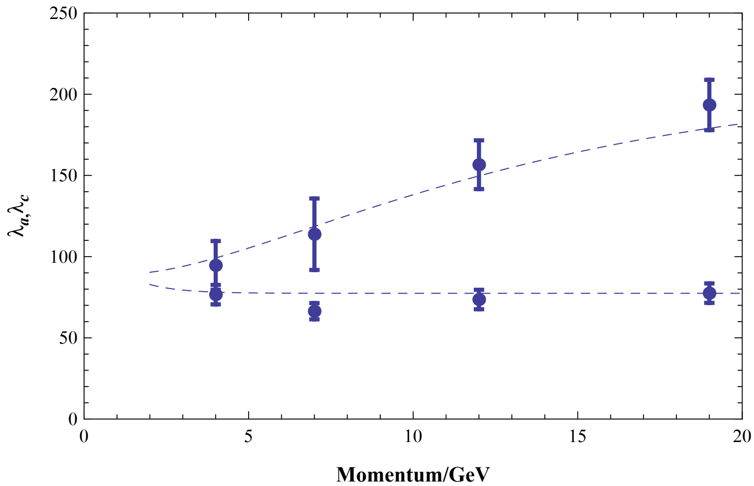

Fig. 9. Comparison of measured (points) and predicted (dotted lines) apparent interaction length (below) resp. cascade length (above) as a function of the proton momentum.

interaction with an energy deposition of at least 150 MeV. The apparent interaction length was measured as the distance to the *first* visible interaction with an energy deposition of at least 150 MeV, whereas the cascade length as the distance to the *last* interaction with an energy deposition of at least 1 GeV, otherwise it does not qualify for a neutral current candidate.

The good agreement between these and other measurements (see Refs. 6 and 42) and their predictions by the neutron background program confirmed the validity of the background evaluation in the discovery paper and dissipated all criticisms as unfounded.

The analysis of the two runs was final by the end of March 1974 and was reported to the APS Meeting[44] at Washington in April 1974.

3.7. *Confirmations*

By Spring 1974 there was ample additional evidence for the existence of weak neutral currents. First of all the Gargamelle collaboration has increased their event samples[45] corroborating the original findings, moreover it confirmed the neutron background calculation by the proton experiment and presented a further independent background determination based on the event position and the different interaction lengths of neutrino and neutron induced events in the chamber.[6, 45] Figure 10 shows a likelihood analysis of the apparent interaction lengths of charged current (CC), neutral current (NC) and associated (AS) events. The CC events are genuine neutrino-induced events and their interaction length is indeed consistent with infinity, whereas the NC events have a shorter apparent interaction length

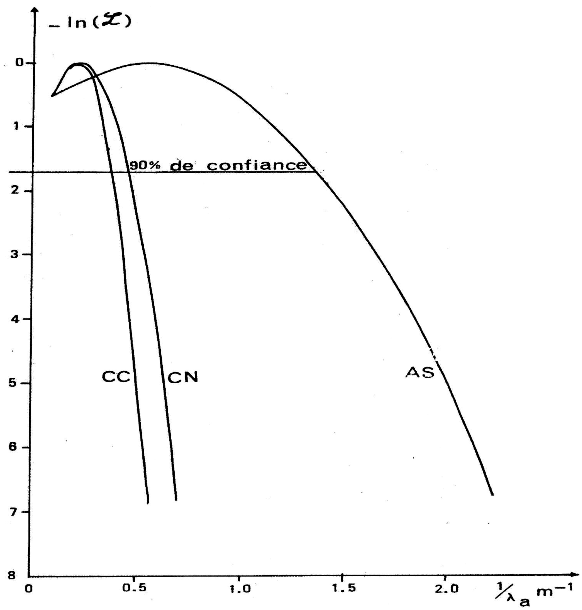

Fig. 10. Log likelihood distributions of charged current (CC), neutral current (CN) and associated (AS) events. The horizontal line indicates the 90% confidence level.

by an amount determined by the contributing neutron component. The estimated amount agrees with the previous direct determination of the neutron background.

The CalTech–Fermilab experiment[46] running in a dichromatic neutrino beam peaking at 45 and 125 GeV has observed a clear signal of muonless events. Charged and neutral current events were distinguished by their event length in the calorimeter. This new method enjoyed many later applications.

A significant number of events ascribed to $\nu n \to \nu p \pi^-$ and $\nu p \to \nu n \pi^+$ has been observed in the 12 ft ANL bubble chamber.[47] This was the first observation of an exclusive neutral current channel.

Finally, the HPW collaboration has understood the reason, why they lost their initial neutral current signal, and came up also with a clear signal.[48]

3.8. *Conclusion*

The Gargamelle collaboration published their discovery in 1973 and stood firm against all criticisms. One year later also the last skeptic was convinced.

The discovery of weak neutral currents initiated a long-lasting boost to high energy physics. The experimental and theoretical investigation of weak neutral currents has led to unprecedented progress on the fundamental scientific frontier as well as in technology and the energy frontier. All this is evident in the retrospect of

40 years. The outstanding achievement is that weak and electromagnetic phenomena are now commonly described by an electroweak gauge theory.

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