The Discovery of Weak Neutral Currents

A Play in 5 Acts*

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Prolog

Weak neutral currents have shaped the physics of the past two decades and represent today a prominent and well tested part of the electroweak theory[1]. The conference here at Santa Monica celebrates the 20ies birthday of their discovery and highlights the heroic times. Its story has been told in many ways, for instance by insiders[2, 3, 4], outsiders[5] and in textbooks[1].

Looking back at the discovery after so many years to the exciting series of events one gets somehow the impression of a *play in 5 acts*.

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ACT 1 – The decade 1960-1970

At the beginning of the 1960s the era of accelerator neutrino physics started at BNL and CERN extending the study of weak interactions into the new and much higher energy regime of a few GeV. Previously nuclear β and elementary particle decays, in particular the π, K and μ decays, were the testing ground of the Fermi theory and reached in the V-A theory a solid phenomenological framework. The universal character of weak interactions strongly suggested the existence of weak spin 1 bosons W^+, W^- as their mediators in analogy to the photon for electromagnetic interactions. Due to the short range action of the weak force the weak bosons, called the *Intermediate Vector Bosons*, would have to be charged and massive.

Two immediate questions waited for an answer from the first neutrino experiments: *Are there two species of neutrinos ?* and *Is there an Intermediate Vector Boson ?* Feinberg (1958) has worried about the strong suppression or absence of the decay $\mu \to e + \nu$ and came up with the conjecture that the neutrino at the μ and e vertices are not identical and that there should be also a light intermediate vector boson. The first question can be answered by building a neutrino beam as proposed by Pontecorvo 1959. Neutrino induced interactions would reveal their nature by observing whether the final state leptons are dominantly muons or a mixture of muons and electrons. Infact, the BNL group found that two distinct neutrinos exist, ν_μ and ν_e, and got confirmed by CERN shortly afterwards. The other question was addressed in two ways by looking for a dilepton signature and for a propagator effect in the energy dependence of the total neutrino-nucleon cross section. No evidence for a carrier of the weak force was found concluding that, if it exists, its mass must be heavier than a few GeV. The search for the *intermediate vector boson* remained one of the main goals for future experiments.

The phenomenological success of the V-A theory, and later the Cabibbo theory, at low energies emphasized the failure to predict non-divergent results. This led theorists to speculate about the high energy behaviour of weak interactions. The rise of the total neutrino cross section would be damped, if a massive *intermediate vector boson W* existed, thus avoiding the unitarity limit, but processes such as $\nu\overline{\nu} \to W^+W^-$ would still remain divergent. It was argued that this divergence could be cancelled by postulating either a *neutral* intermediate vector boson in addition to the charged ones or a *heavy lepton* leading to novel types of neutrino interactions. The known neutrino interactions were from now on called *charged current* interactions (*CC*), the postulated new ones *neutral current* interactions *(NC)*. The prime importance of the question challenged immediate searches by looking in ν-induced events for final states *without* μ and by looking for *flavour changing decays*, i.e. decays with no change in the electric charge (ΔQ=0) *and* a change by one unit in strangeness ($\Delta S = \pm 1$). None of the searches hinted at evidence for weak neutral currents. The discouragingly low rate of flavour changing neutral current decays remained a puzzle until the GIM mechanism was proposed 1970. Anyway, the negative results related to the neutral current searches were turned into upper limits. The experimentalists lost interest and focussed on the investigation of the charged current processes in the new energy regime.

The 60s are characterized by vigorous progress in the new domain of neutrino physics with the brilliant prospect for a long term program using larger detectors in preparation at several laboratories (CERN: Gargamelle, BNL: 7 ft, NAL: 15 ft, ANL: 12 ft and HPWF) and upgraded neutrino beams. The known problems in the weak interaction phenomenology raised a great variety of theoretical activities such as the unification of electromagnetic and weak interactions, renormalization, spontaneous symmetry breaking, current algebra. Important developments took place in parallel to weak interactions as well. 1964 CP violation was discovered. The *8-fold way*, the idea of quarks as constituents of the hadrons, current algebra were driving forces on the way to the understanding of strong interactions. Particular interest attracted the observation at SLAC of the substructure of the nucleon and scaling behaviour in the process $ep \rightarrow e + anything$. These new prospects influenced the preparation of the neutrino program for Gargamelle.

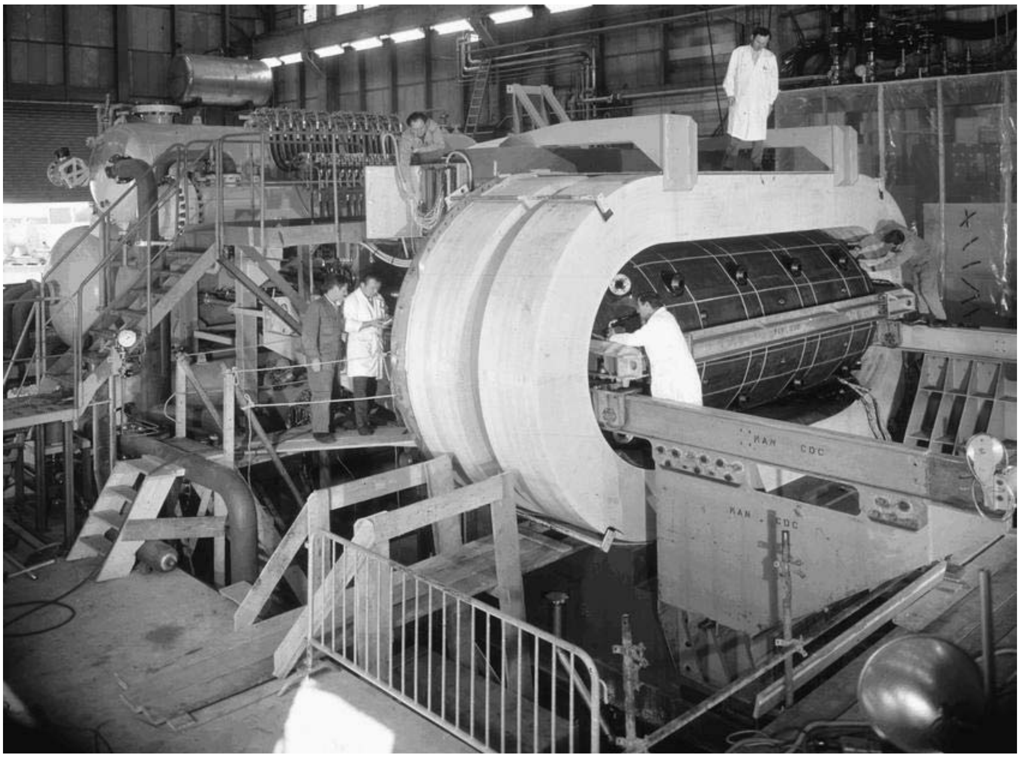

Figure 1: The body of Gargamelle is inserted into the magnet coils.

ACT 2 – Gargamelle

Shortly after the Siena Conference 1963 a large heavy liquid bubble chamber, later called *Gargamelle*, was proposed and motivated by the search for the intermediate vector boson W. Having an order of magnitude larger size it would ensure improved performance in many respects:

- Large target mass: increased number of events
- Large potential path: increased detection efficiency for charged hadrons
- Short radiation length: high detection efficiency for e^+, e^-, γ
- Different choices of heavy liquids: CF_3Br, C_3H_8

Lagarrigue and his group conceived and built the chamber. When the future physics program of Gargamelle was discussed 1968 at Milan the search for neutral currents did not play any rôle, it was not even mentioned. In the proposal [6] for the first neutrino run the search for the W had still highest priority, although the really hot issues were related to the question whether or not the structure of the nucleon as seen by the W and by the γ agree with each other.

The rich life of Gargamelle lasted 8 years. Figure 1 shows the chamber body at the moment, when it was mounted inside the magnet coils. The first expansion took place in December 1970. From then onwards the chamber ran for most of its lifetime at the CERN PS and for a short while at the SPS, until it broke down 1978.

The pictures taken in the first exposures in 1971/2 were evaluated immediately by the 7 laboratories. The scanning proceeded according to rules defined well ahead of the start and benefited from the experience gained in the runs with the NPA 1m bubble chamber. The events were classed in 5 categories. Here the first three are of interest. The events with a μ^--candidate[1] fell in category A. Since the bubble chamber was not equipped with a μ detecting device, any event with a negatively charged particle leaving the chamber without visible interaction was indistinguishable from a genuine μ^- and contributed also to category A. Thus the category A events included an unavoidable background, which had to be determined and subtracted. The standard procedure to cope with this background consisted in collecting those events in category B, where the final state particles did definitely not contain a muon, and in category C, where the final state was made up of protons only. Then, with the knowledge of the π^- interaction length in the liquid the probability for a π^- to leave the visible volume of the chamber, and thus to fake a μ^-, can be calculated without any need for Monte Carlo techniques.

Category B got contributions from energetic neutrons entering in beam direction the chamber and interacting in the fiducial volume. Such neutrons arise as secondaries from upstream ν-interactions, so this category is definitely not empty. If weak neutral currents events should exist, they would automatically be part of the category B. This was the reason, why the Gargamelle Collaboration could, at any moment, launch a neutral current search. In fact, in spring 1972 the Milan group investigated the distribution along the chamber of the class B events and observed to their surprise a flat behaviour rather than the expected exponential falloff characteristic of neutrons with the typical interaction length of 70 cm in the chamber liquid freon. This was the trigger to start a dedicated search of the events in category B, now called the neutral current *candidates*. A strong energy cut was imposed on their final state for a better discriminaton against the neutron background. For comparison a subsample of charged current candidates from category A was selected which had to satify the same criteria regarding their hadron final state.

During the intense period of searching for neutral currents an exciting event[7] was found at Aachen. It consisted of just an isolated electron in beam direction. Since it could not be explained by any conventional mechanism it was interpreted as candidate for a purely leptonic neutral current interaction : $\overline{\nu}_\mu e \to \overline{\nu}_\mu e$.

The situation as of early Spring 1973 can be summarized as follows: The event samples are reported in Table 1, while Figure 2 displays some geometrical

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

Table 1: Number of candidates

[1] This holds for the ν exposure, for the $\overline{\nu}$-exposure the charge signs are opposite.

distributions. One of the most prominent candidates among the muonless events

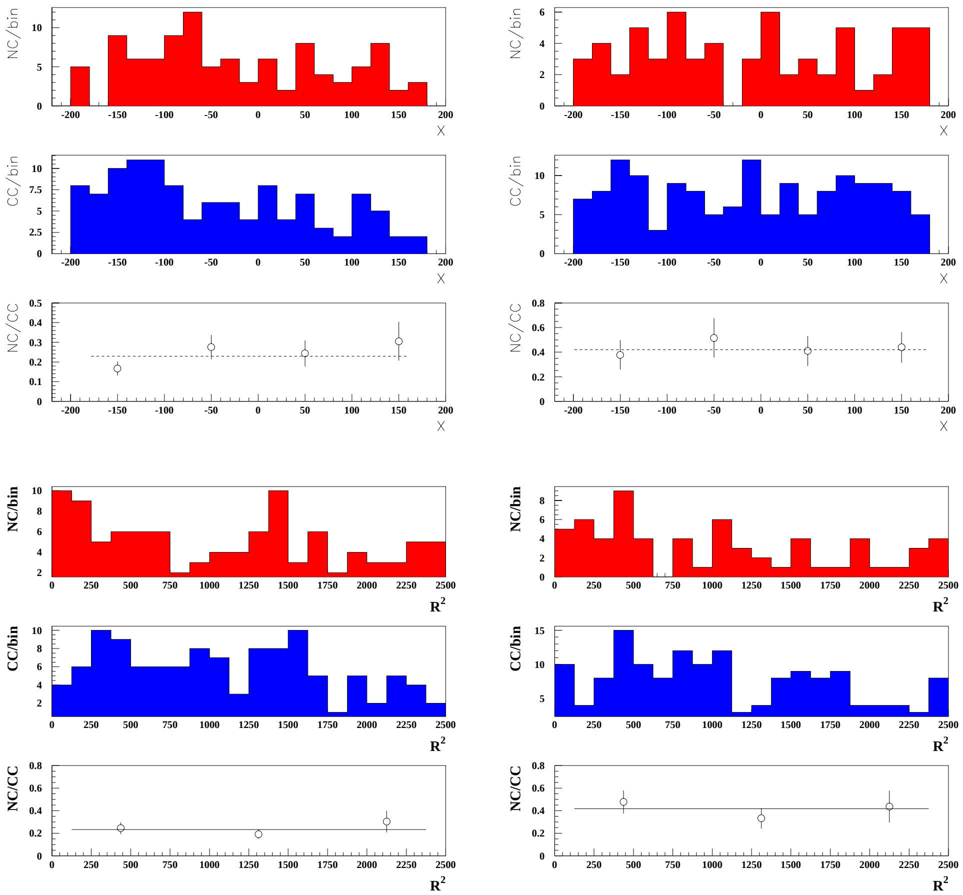

Figure 2: Geometrical distributions: X measures the distance along the chamber, R measures the radial distance

is shown in Figure 3.

The arguments in favour of the hypothesis that the NC candidates are ν-induced, were :

1. The large number of candidates.

2. The distributions in X, R^2, E_{had}, $\cos\theta$ looked similar for neutral (NC) and charged (CC) current candidates.

3. Since the neutron interaction length in the chamber liquid (70 cm) was small compared to the chamber dimensions, the longitudinal vertex distribution of the NC candidates should exhibit the typical exponential falloff, if due to neutrons. However, on the contrary, the distribution looked rather flat, as would be expected for ν-induced interactions.

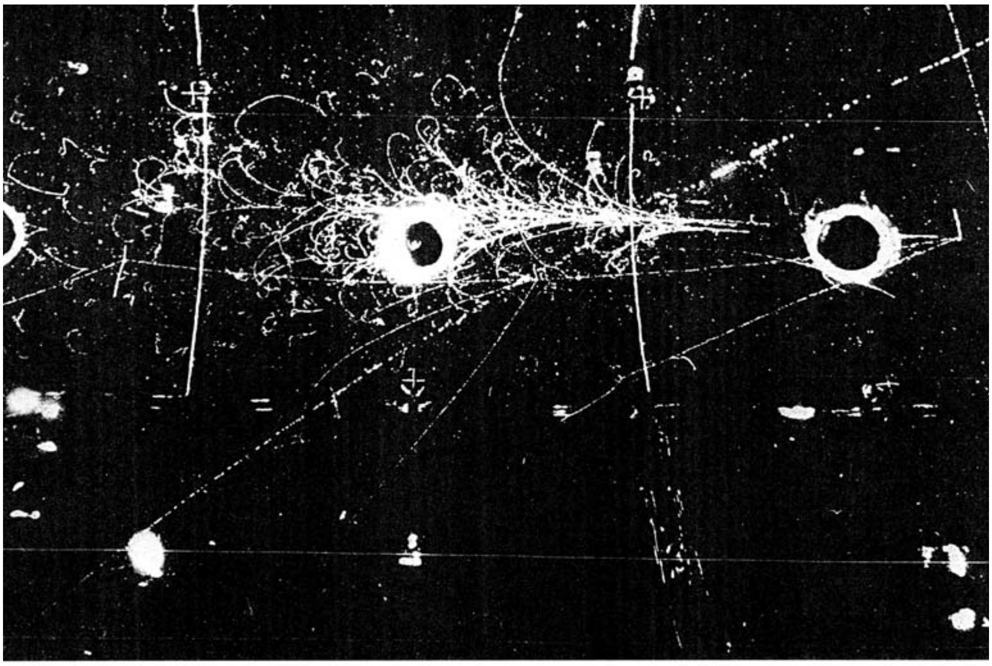

Figure 3: A prominent neutral current candidate: the neutrino enters from the right side.

These arguments were supported by the Monte Carlo simulation of the Orsay group based, though, on simplifying assumptions.

ACT 3 – Neutrons or Neutrinos ?

The method of establishing a genuinely new effect consists in the explicit exclusion of all known explanations. Events which then remain unexplained are attributed to something new. This means all efforts must be concentrated on the discussion of all possible background sources. In the search for *weak neutral currents* it was quickly recognized that the only serious background would come from neutral hadrons, i.e. neutrons and neutral K-mesons, a conclusion which was reached already in previous searches within the 1m NPA bubble chamber experiment.

The euphory within the Gargamelle Collaboration was large, because it was clear that a great discovery is imminent. However, it was also clear that the Collaboration faced a large responsibility. The *yes* or *no* would be decisive for the proposed Glashow-Salam-Weinberg model, in which weak neutral currents are at heart.

This state of euphory in March 1973 was abruptly damped, when Fry and Haidt put forward a new and dangerous argument, namely the fact that fast nucleons generate a *cascade*. The cascade hidden in the shielding is a danger, because the cascade length increases with energy and so does the neutral hadron background. The number of neutrino interactions per unit length in a given medium is roughly a constant when the nuclear interaction length is taken as unit. Thus the event density per 70 cm in the bubble chamber liquid is about the same as the one in 15 cm of iron in the shielding in front of the bubble chamber. Energetic neutrons emitted in neutrino interactions have a chance to enter the chamber volume not just when they originate from the chamber wall, but via cascading also from deep in the shielding upstream. In addition the cascade hidden in the shielding may be carried by any hadron, since what is observed in the chamber is only the *end* of the cascade. For example, a neutron of 5 GeV has a cascade length of about 5 times the nuclear interaction length. As a consequence, without taking into account the cascade effect the neutral hadron background is underestimated and the claim to see a new effect not obvious.

Another aspect must be considered. The layout of the Gargamelle experiment (see Fig. 1) shows that a large fraction of the chamber volume is invisible and, more importantly, the chamber body is surrounded by the coils and the magnet yoke, thus by heavy material which acts also as neutron sources, since the neutrino flux has a lateral profile extending well beyond the fiducial volume. The neutrons are generated in ν-interactions with a certain angular distribution. This means that even neutrons originating from the material along the chamber are enabled to enter sideways the fiducial volume of the chamber.

In conclusion, the resulting shape of the vertex distribution from neutron induced interactions in the fiducial volume gets two contributions, the notorious exponential falloff from upstream sources and a uniform distribution from sources at the side. Thus, there is a priori no longer a distinctive feature between n- and ν-induced interations, unless by a *quantitative* calculation the proof is given that the number of n-induced interactions is a small fraction of the NC candidates *despite* the cascade effect.

This proof was achieved within three months and is described in detail in ref. [14]. Given the complexity of the problem a Monte Carlo method was the appropriate approach. Three ingredients were needed :

1. Geometry: Description of the experimental setup including the detailed matter distribution

2. ν-flux: Energy and radial flux distributions

3. Cascade: Dynamics of the hadronic final state

The code was conceived in modular form to ensure flexibility and transparency. The geometry of the chamber and the different materials such as the chamber liquid (visible and invisible parts) and the walls, the coils, the shielding were carefully incorporated, the measured ν-flux as well. The treatment of the hadrons generated in ν-interactions represented the critical and nontrivial aspect of the problem, since they give rise to a cascade. Although cascade calculations were known for their limited reliability, the present approach is robust, because the NC candidates were required to have visible energy in excess of 1 GeV. Consequently only a neutral hadron, i.e. a neutron or K^0, energetic enough to deposit in the fiducial volume 1 GeV or more must be considered. Since the ν energy spectrum is effectively cut off at 10 GeV, it follows further that the mesonic component of the final state cascade is inactive and that at best *one* nucleon is cascading. Therefore, the cascade is *linear* and can be characterized by a single quantity, the *elasticity* (see details in ref. [14]).

The first results in May 1973 gave hope to a reliable prediction. Next, the required shape of the elasticity distribution was derived from published data on nucleon-nucleon resp. nucleon-nucleus scattering which were available in the energy range of interest. As a matter of fact, the shape could be checked directly with the actual event sample. Neutron interactions are observed in two topologies, namely as

- **B-event**:
  the neutron interaction in the fiducial volume is the *end of the cascade* originating from neutrino interactions upstream

- **AS-event**:
  the *beginning of the cascade* originating from a neutrino interaction occurring in the fiducial volume of the chamber and followed by an associated downstream neutron interaction

Thus the elasticity distribution is constrained for small and large values by the events themselves. Of particular importance is the behaviour at large elasticities, since quasielastic interactions give rise to little energy deposition, mostly just a recoil proton, which, if not observed, leads to an *effectively* increased interaction length. Cascades consisting of several steps were too rare to be observed in the small sample of AS events due to the limited remaining potential path in the visible part of the chamber.

The sample of associated events (AS) became final only at the beginning of July 1973. By that time the program to predict the neutral hadron background including the cascade was also ready and its implications were studied by varying all sensitive ingredients. The prediction had no free parameter.

The cascade program served in several ways. In the first application the worst possible case was considered, namely the **hypothesis : All NC candidates are neutral hadron induced** or equivalently assuming #B = #NC. Therefore, the ratio B/AS should be 102/15 for the ν-experiment and 64/12 for the $\overline{\nu}$-experiment. Furthermore, the parameters defining the angular and energy distributions of the background events were to be chosen such as to reproduce those of the NC candidates. The shape of the energy distribution was well described by $dN \approx E^{-n}dE$, while the angular distribution $dN \approx e^{-\theta^2/2\theta_0^2}dcos\theta$. Agreement with the data was achieved for $n = 1.1 \pm 0.3$ and $\theta_0 = 0.35 \pm 0.05$. Then the ratio B/AS was predicted to be

$$\frac{B}{AS} = 1.0 \pm 0.3$$

in striking contradiction to the assumed ratios of $102/15 = 6.8 \pm 1.9$ and $64/12 = 5.3 \pm 1.7$. Thus, the hypothesis must be rejected. This was the breakthrough reached by the middle of July 1973 and formed the safe basis for claiming the discovery of *ν-induced μ-less events*[8], then interpreted as evidence for weak neutral currents. Having rejected the above hypothesis the next important application of the program consisted in evaluating the *best* estimate of the B/AS-ratio under the actual experimental conditions with the result 0.7 ± 0.3.

Another way to estimate the neutron background was the attempt of Baldi and Musset in their *shell method*, which consisted in comparing event rates and geometrical properties in the visible (outer shell) with those in the fiducial volume (inner shell) of the chamber. No quantitative result was obtained, because of the uncertainty in the smooth transition to the much larger invisible volume surrounding the illuminated part.

Perkins[2] and Rousset[9] established compact formulae for the ratio B/AS, where the details of the geometrical and dynamical properties are characterized by suitable averages entering as global free parameters. These formulae were extensively used in discussing qualitative features. The cascade program provided the quantitative basis for their applicability.

Finally, and of vital importance, the program served to answer all critical questions raised by the collaboration before publication at the end of July 1973. This was readily possible due the modular structure of the code. By anticipating even extreme and unrealistic assumptions about the neutral hadron background the collaboration was well prepared to critics it might, and sure enough did, face when defending afterwards the discovery.

Pullia[10] has applied the Bartlett method to the CC, NC and AS events, which consists comparing for each event the flight path with its potential path in the chamber. The critical element of the method is the determination of the flight direction, which relies on the actually measured final state 3-momenta. Fig. 4 shows the result of the maximum likelihood analysis and supports the conclusion

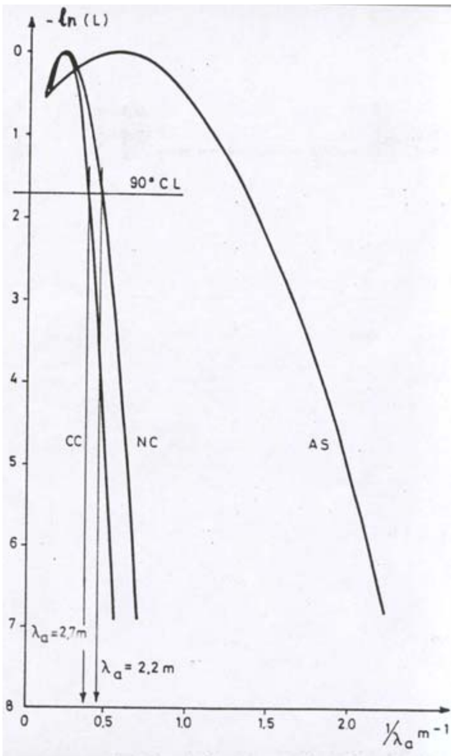

Figure 4: Maximum Likelihood distributions of NC, CC and AS events

that the NC events were not dominated by neutron interactions.

Myatt has presented the discovery of *μ-less events* by the Gargamelle Collaboration at the *Bonn Electron-Photon Conference* at the end of August 1973 together with the results from the HPWF Collaboration[4]. In his concluding remark C.N.Yang announced as the highlight of the conference the observation of weak neutral currents.

ACT 4 – Critique - Crisis

The title expresses in nuce the dramatic months following the publication of the discovery. The meaning of the word *critique* is clear, while *crisis* should be understood in the greek sense intending a *change to the worse or the better*.

While the Gargamelle collaboration continued their research collecting more statistics, the HPWF collaboration prepared a new run with a modified setup. Soon after, it became known that the HPWF collaboration did not see anymore the neutral current effect in their new detector configuration[4]. This in turn caused critical questioning to the Gargamelle collaboration. The obvious argument against Gargamelle was to have underestimated the neutron background, thus casting doubt on the treatment of the neutron cascade.

As a way out of this crisis not only for the Collaboration, but also for the laboratory CERN itself, Gargamelle was exposed in November 1973 to monchromatic proton bunches by operating the CERN PS in a rapid beam deflection mode. The chamber was filled with the same liquid freon as before. The direct observation of the proton cascade should serve as a unique check of the neutron background calculation. To this end the behaviour of the proton induced cascade

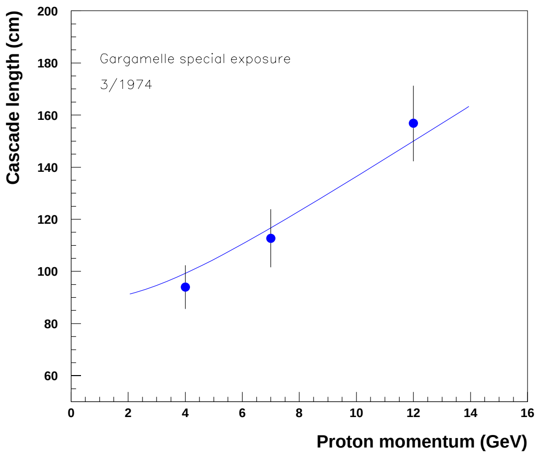

Figure 5: Measured and predicted proton cascade length versus proton momentum.

inside Gargamelle was predicted before hand using the same cascade program as for the already published discovery paper. This prediction had no free parameter except for the choice of the incoming proton momentum. Exposures with four momenta, namely 4, 7, 12 and 19 GeV were carried out in order to measure the characteristics of the proton cascade, in particular to obtain the energy dependence of the cascade length λ_C. The four runs were evaluated during the winter months and the results were reported to the meeting of the American Physical Society (APS) at Washington in April 1974[11]. Fig. 5 illustrates the agreement

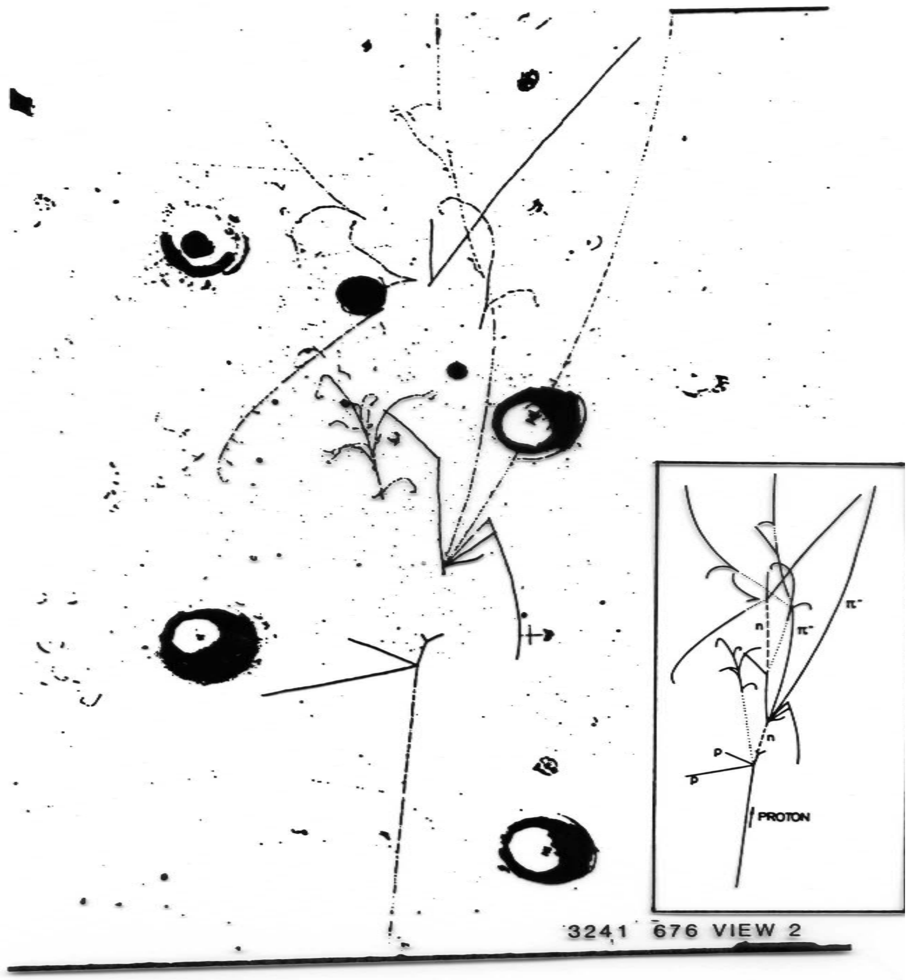

Figure 6: Proton cascade observed in Gargamelle. A 7 GeV proton enters from below and generates a cascade as interpreted in the inserted sketch.

between the measured and predicted cascade lengths and demonstrates beyond any doubt that the calculation of the neutron background was indeed *reliable* as claimed. Together with the results on the cascade properties of the special exposure also an update of the statistics in the Gargamelle neutral current experiment (see table 2) has been reported to the *APS* Meeting.

The cascade program was applied successfully in several subsequent experiments with Gargamelle and BEBC to calculate the neutron background.

ACT 5 – Happy End

After the hot fall 1973 the progress until the High Energy Conference at London 1974 was enormous. Ample evidence then existed for weak neutral currents from four experiments.

1. **Gargamelle**
   The Gargamelle Collaboration had doubled the statistics and found good agreement with the previously published results.

# events/film	B O N N (8/73)	W A S H I N G T O N (4/74)
$\frac{\#NC}{film}\nu$	$\frac{102}{111} = 0.92 \pm 0.13$	$\frac{191}{197} = 0.97 \pm 0.10$
$\frac{\#NC}{film}\overline{\nu}$	$\frac{63}{276} = 0.23 \pm 0.03$	$\frac{70}{298} = 0.23 \pm 0.10$
$\frac{\#AS}{film}\nu$	$\frac{15}{111} = 0.14 \pm 0.04$	$\frac{40}{277} = 0.14 \pm 0.03$
$\frac{\#AS}{film}\overline{\nu}$	$\frac{12}{276} = 0.04 \pm 0.01$	$\frac{14}{328} = 0.04 \pm 0.01$

Table 2: Progress of Gargamelle within one year

2. **HPWF**
   The HPWF collaboration had understood why the effect disappeared and has now also convincing evidence for neutral currents.

3. **ANL**
   The *12-foot* Argonne bubble chamber reported single pion production induced by neutral currents[12].

4. **CITF**
   The CITF Collaboration performed a new calorimeter experiment and reported the observation of neutral current events in deep inelastic scattering based on a new method[13]. The evidence for neutral current events was derived from the event length distribution.

In conclusion, a new chapter in physics was opened. The discovery of weak neutral currents had a worldwide impact on the research programs. It influenced deeply the high energy fixed target physics (νe, νN, ep, μN), e^+e^-- and $p\overline{p}$-collider physics, atomic physics, astrophysics and cosmology. The discovery paved the way towards the *electroweak* theory.

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