

## WEAK NEUTRAL CURRENTS DISCOVERY: A GIANT STEP FOR PARTICLE PHYSICS

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\* DOI: 10.1051/ePN/2010103

*Subatomic particles interact with different kinds of forces (strong, electromagnetic, weak and gravitational). In case of the weak force, the interaction is due to the exchange of intermediate charged ( $W^{+-}$ ) and neutral ( $Z^0$ ) bosons. These cases are referred to as “charged currents” and “neutral currents”, respectively. When evidence for such ‘Weak neutral currents’ was first published in 1973 the high energy physics community was incredulous.*

It took the community a year to acknowledge the discovery. But this discovery, perhaps the most important made at CERN, was the onset of a new era in our understanding of fundamental interactions. Thirty-six years after the discovery, the 2009 EPS Prize for High Energy and Particle Physics was awarded to the Gargamelle<sup>1</sup> Collaboration for the observation of the weak neutral current interaction [1,2]. The award ceremony took place at the EPS-HEP 2009 Conference [3] in Krakow (Poland). The story of the discovery shows how difficult sometimes it can be to drastically change widespread beliefs.

### Elementary particles and their interactions, now and before

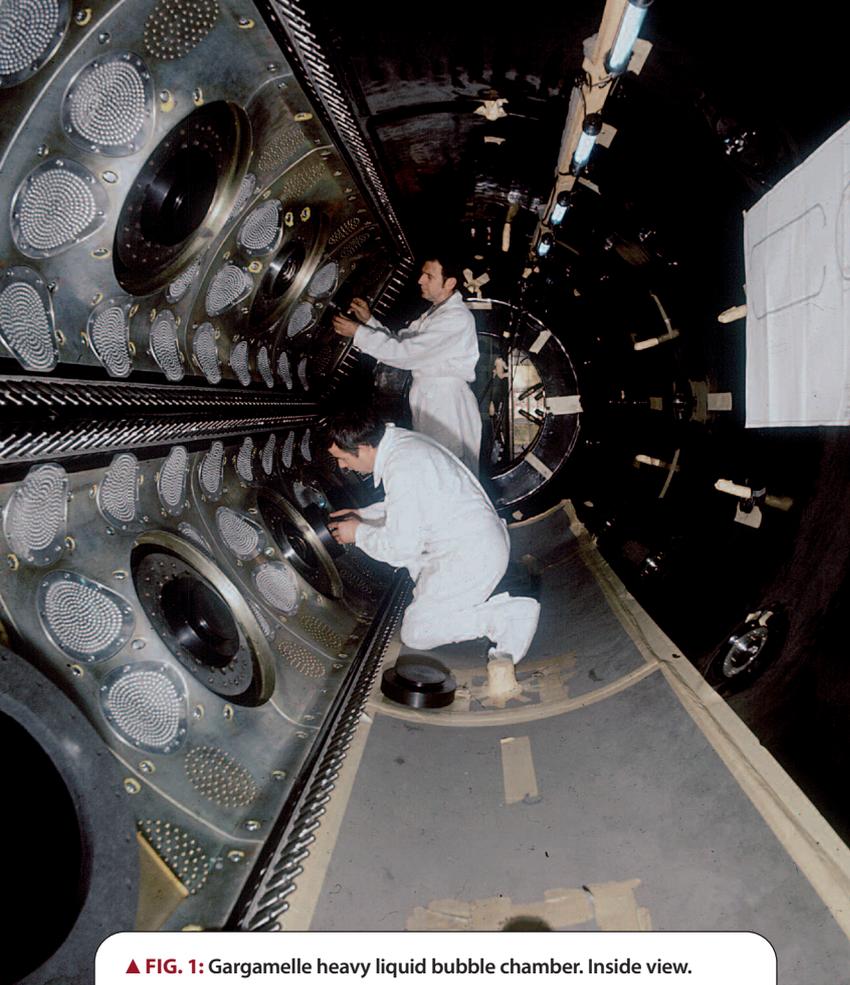
All phenomena observed so far in Nature are understood as manifestations of the ‘elementary world’. In our current understanding the microscopic world is made of 2 families of so-called “elementary” particles (6 leptons and 6 quarks) interacting via 4 fundamental

interactions: the strong, electromagnetic, weak and gravitational forces. In today’s theory, the so-called Standard Model (SM), the first three interactions are described by the exchange of spin-1 gauge bosons: strong interactions are mediated by gluons, electromagnetic interactions by photons, weak interactions by charged ( $W^{+-}$ ) and neutral ( $Z^0$ ) massive vector bosons. Gravitational interactions are still not well understood at the microscopic level but there is a general belief that the mediator is the graviton (a spin-2 particle). In the late 60’s, only the electromagnetic interaction mediated by the photon was really well understood and described by the Quantum ElectroDynamic theory (QED). Weak interactions were understood in terms of the so-called Fermi theory, proposed in 1934 by Enrico Fermi [4] and modified in the late 50’s to account for parity violation. This theory was a local theory, in the sense that the weak interaction was not mediated by exchange of a vector boson which propagates: it was a

▲ the whole Gargamelle setup © CERN

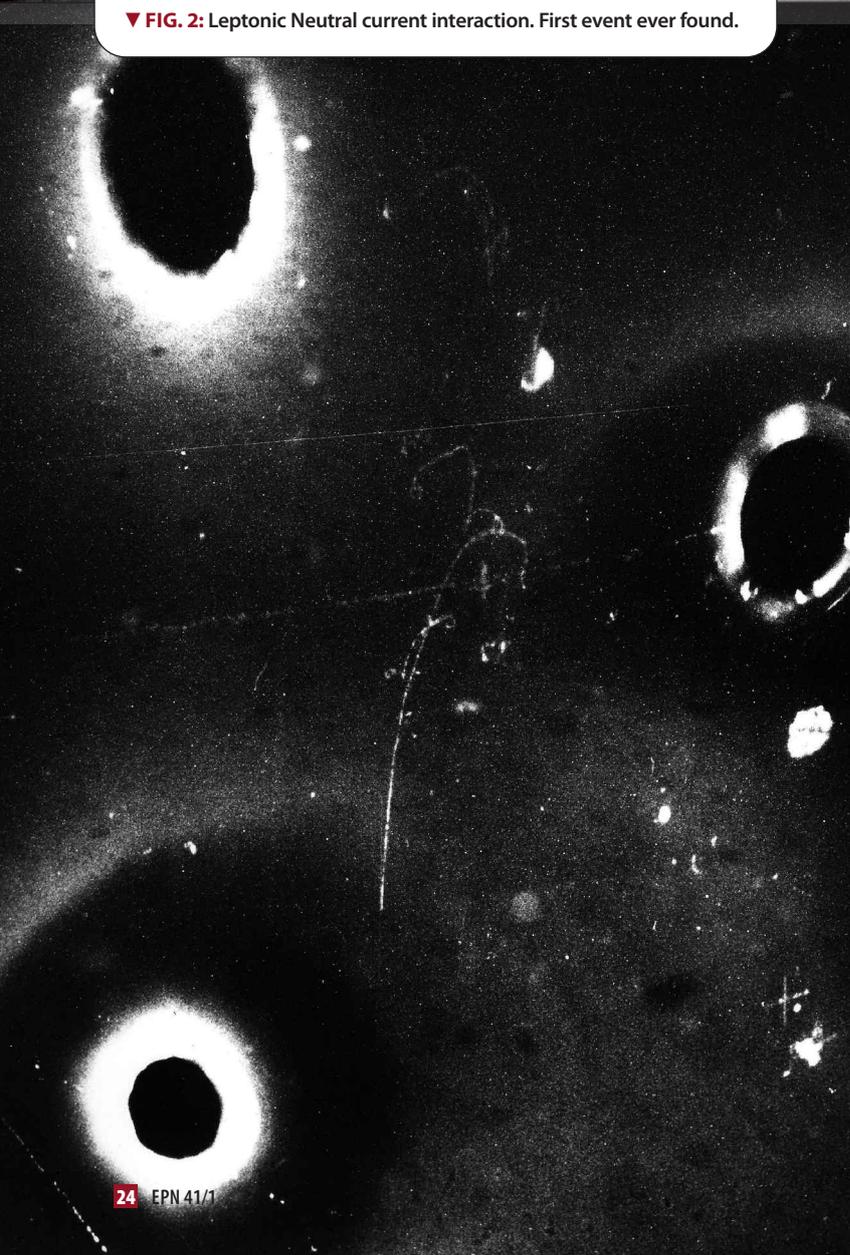
#### note

<sup>1</sup> Gargamelle was chosen as the name for the giant bubble chamber, after the giant mother of Gargantua in novels by François Rabelais (16<sup>th</sup> century).



▲ FIG. 1: Gargamelle heavy liquid bubble chamber. Inside view.

▼ FIG. 2: Leptonic Neutral current interaction. First event ever found.



point-like interaction. Low-energy processes, such as neutron beta-decay (in which a neutron decays into a proton, an electron and an antineutrino), or muon decay (in which a muon decays into an electron, a muon-like neutrino, and an electron-like antineutrino) were quite well described by this theory. However, everybody knew that this theory could not work at high energy since it has divergences (prediction of infinite cross-sections at high energy).

The Standard Model introduced by A. Salam, S.L. Glashow and S. Weinberg in 1967 [5] allowed to overcome this problem, and even more, to propose a unified theory of weak and electromagnetic interactions. But it needed the existence of the weak neutral current interaction.

In weak interaction processes observed at that time, a charged lepton was always associated with a neutral lepton (hence a “charged current”). Strange particles were also known, and their observed decay had the same property. There were on the contrary very strong experimental bounds on decay modes such as for the  $K^+$  meson into a charged pion, a neutrino and an antineutrino (with a pair of neutral leptons, hence the name “strangeness-changing weak neutral current”). As a consequence, at the beginning of the sixties there was a widespread belief that neutral current interactions, with strength comparable to the charged current ones, could not exist.

### The birth of the Gargamelle project

For a precise and detailed study of weak interactions, the neutrino is an ideal probe since it is not sensitive to any other kind of interaction. The project to build a giant heavy liquid bubble chamber to study in-depth neutrino interactions, and thus weak interactions, was born at the Sienna conference in 1963 from a discussion between Profs. André Lagarrigue and Luis Alvarez. The driving ideas were i) a huge target mass for statistics ii) a long enough path in the liquid to detect and identify all particles going out of the primary interaction vertex and their secondaries. The projected bubble chamber was called Gargamelle, from the name of the giant mother of Gargantua in novels by François Rabelais (16<sup>th</sup> century). After an agreement in 1965 between the CEA-Saclay for building the chamber, and CERN to operate it in a neutrino beam, the Gargamelle collaboration was formed in 1967 by seven laboratories: Aachen, Brussels, CERN, Paris, Milano, Orsay and London. Gargamelle was designed and built under the leadership of André Lagarrigue, and assembled and operated at CERN (fig. 1) by a team including Paul Musset and André Rousset. But in the White report written by the collaboration to establish a shopping list of reactions to study, the neutral currents had only the 10<sup>th</sup> priority!

## Exciting news for weak interactions theories

In the late 60's and early 70's, some important theoretical developments boosted the interest in the search for weak neutral currents. The Glashow-Weinberg-Salam theory of electroweak interactions among leptons predicted the existence of a massive neutral weak boson [5]. The Glashow-Iliopoulos-Maiani (G.I.M.) mechanism was explaining, via the introduction of a hypothetical heavier fourth quark (charm, in addition to up, down and strange), the suppression of strangeness-changing neutral currents, while permitting strangeness-conserving ones [6]. The proof of renormalizability (to avoid divergences) for such theories by 't Hooft and Veltman [7] in 1971 led particle physicists to take the G.I.M. predictions more seriously and revived the interest of the Gargamelle collaboration for neutral currents. Furthermore new calculations about semileptonic Weak Neutral Currents [8,9,10] were published.

## Neutral currents hunting is opened

In a collaboration meeting in March 1972 the Milano group showed the first hints of neutral currents in neutrino interactions with at least one pion outgoing. It was immediately decided to put the highest priority on the search for neutral currents among the million pictures to be taken with the Gargamelle detector and its 12 cubic meters of liquid heavy Freon  $\text{CF}_3\text{Br}$  in the neutrino/antineutrino beam at CERN. The chamber was ideally suited for this search due to its very high particle identification capability. Since the beam at CERN consisted mainly of muon-like neutrinos and antineutrinos, neutral currents could manifest themselves in muon-neutrino elastic scattering off electrons (purely leptonic neutral current), or neutrino scattering off nuclei of liquid freon without prompt muon or electron in the final state (semi-leptonic neutral current).

The first beautiful, but not yet conclusive, hint of such interactions was an event observed in Aachen around Christmas 1972, an isolated electron compatible with the interpretation of muon-neutrino elastic scattering off electrons (fig. 2).

The semi-leptonic neutral current interaction (so-called hadronic events) had a much higher probability to occur. However, they could be simulated by background reactions, mainly interactions in the liquid of high-energy neutrons produced in neutrino interactions out of the visible volume (fig. 3 a charged current event, and fig. 4 a neutral current event). The collaboration worked hard to get reliable and safe estimates of this background using simulations, calculations based on equilibrium arguments, and an evaluation of the apparent interaction length of the events. A direct mea-

surement of the neutron's behaviour in the chamber by an exposure of Gargamelle to a proton beam was also performed.

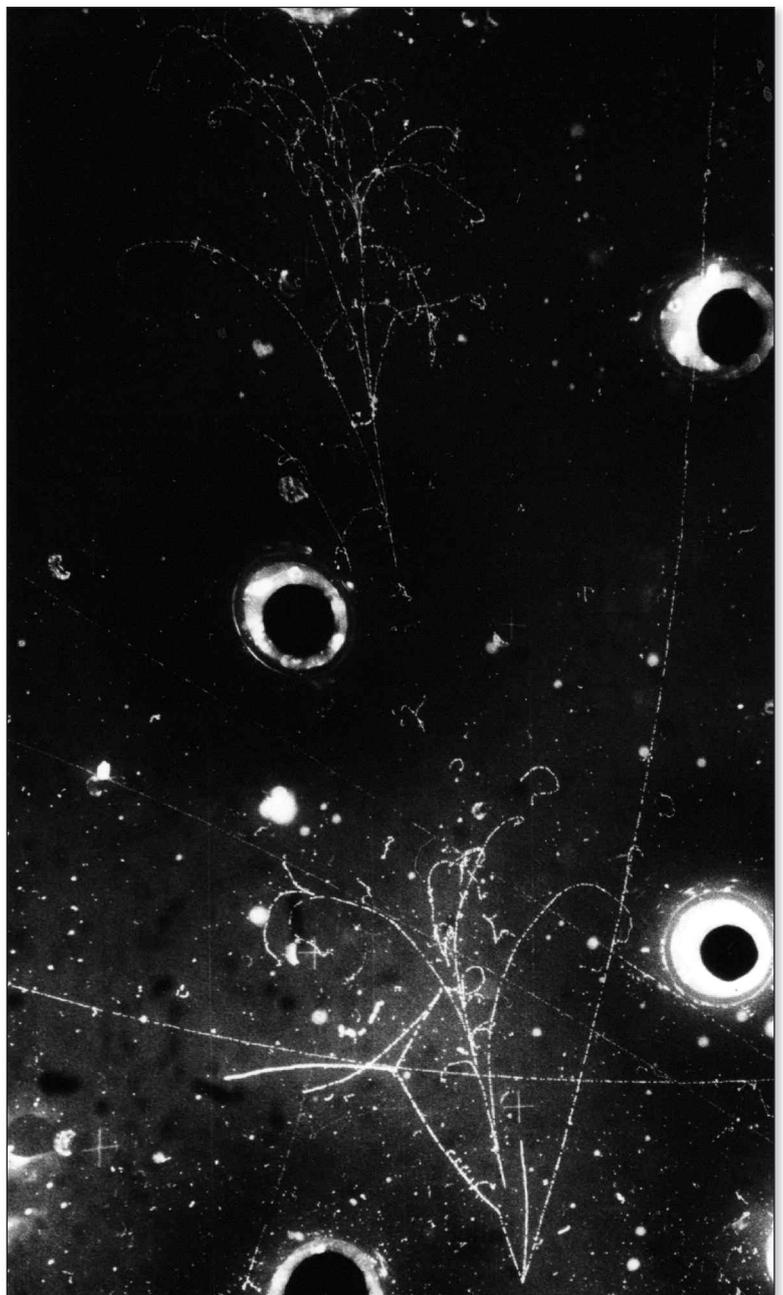
Eventually, the collaboration was convinced that the result was solid and reliable.

After a seminar by Paul Musset at CERN in July '73, the first evidence for both leptonic and semi-leptonic neutral currents was published by the collaboration in the same issue of Physics Letters in September 73 [1, 2]. 55 physicists, from groups at Aachen, Brussels, CERN, Paris, Milano, Orsay and London signed the discovery.

## Epilog

The high energy physics community reacted incredulously to the announcement of the discovery. Around the same time a neutrino experiment in Fermilab (HPWF) claimed that they do not see neutral currents.

▼ **FIG. 3:** A charged-current event. The track on the right leaves the chamber without any interaction, identifying it as a muon with high probability.



So, for months people thought that the result was dubious. Fortunately, in early '74, two new leptonic neutral current candidate events were found in Gargamelle films, reinforcing the confidence of the collaboration in their result. Eventually, the Fermilab experiment, after modifying their apparatus, confirmed in summer '74 the result of Gargamelle [11] and another experiment (CITF) showed an irrefutable evidence of the existence of Neutral Currents [12].

▼ **FIG. 4:** A so-called "semi-leptonic neutral current". All the tracks interact in the liquid, signifying that there is no muon, and so no charged lepton outgoing.

Soon after the discovery of Neutral Currents, the fourth quark predicted by the GIM mechanism was discovered simultaneously at BNL [13] and at SLAC [14] in the USA. The electroweak theory was quickly recognized, and Nobel prizes were awarded to Glashow, Salam and Weinberg in 1979, for their theoretical work. Gargamelle was left in the shadow, very likely due to the sudden death of André Lagarrigue in early '75. In 1983,

the intermediate weak bosons  $W^+$ ,  $W^-$  and  $Z^0$  were discovered at CERN, putting a final touch to the story.

Many experimental measurements have now been performed, on a large field of physics phenomena, and the continuing agreement with the Standard Theory has been used to put more and more stringent bounds on possible new physics beyond the Standard Theory. Thirty-six years after its discovery, the weak neutral current interaction remains the most recent fundamental interaction to have been unambiguously observed. Thanks to the European Physical Society, this exciting endeavor has been revived. ■

### Authors biography

**Jean-Pierre Vialle**, Laboratory of Annecy-le-Vieux of Particle Physics (LAPP), Université de Savoie and CNRS/IN2P3. After Gargamelle, he worked on the UA1 experiment at CERN and signed the discovery of the intermediate weak bosons  $W^+/W^-$  and  $Z^0$ . Since 1996, he is working on astroparticle physics. Now he is head of the AMS space experiment project in France.

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