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Science in the making 2: From 1940 to the early 1980s / *La science en mouvement 2 : de 1940 aux premières années 1980*

André Lagarrigue: From cosmic rays to the discovery of the weak neutral currents

André Lagarrigue : des rayons cosmiques à la découverte des courants neutres de l'interaction électrofaible

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A R T I C L E   I N F O

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A B S T R A C T

André Lagarrigue's scientific career is intimately related to the development of elementary particle physics, from pioneering studies with cosmic rays to the discovery of weak neutral currents. His experience in building detectors, culminating with the construction of large heavy liquid bubble chambers, his vision of the best experimental paths, and his enthusiastic leadership have strongly contributed to the progress of the field. The discovery of weak neutral currents with the giant Gargamelle bubble chamber was the first major step in establishing the Standard Model of the fundamental interactions based on gauge theories.

R É S U M É

La carrière scientifique d'André Lagarrigue se situe à une période charnière, qui voit la naissance de la physique des particules élémentaires et le chemin expérimental et théorique menant au modèle standard des interactions fondamentales. Par son expérience de constructeur d'appareillage, qui culmine avec les grandes chambres à bulles à liquide lourd, sa vision de la physique et son autorité naturelle, Lagarrigue a contribué grandement à ces développements. Sa contribution majeure est la découverte des courants neutres faibles avec la chambre géante Gargamelle, qui a apporté une vérification cruciale de l'interaction électrofaible dans le modèle standard basé sur des théories de jauge.

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1. Early particle physics in France

1.1. The situation of particle physics in the 1940s

The aim of particle physics is to discover and study the basic constituents of matter and the fundamental interactions between them. This science field emerged naturally from early discoveries and progress in nuclear physics when, in the first two decades of the 20th century, the atoms were resolved as massive pointlike nuclei surrounded by electrons. A new step was achieved in the thirties with the discovery of the neutron and the understanding of the basic structure of the atomic nucleus made of protons and neutrons. One can say that the real start of particle physics occurred in 1928 with the Dirac equation, describing both particles and antiparticles with spin $\frac{1}{2}$. It was indeed followed by the discovery of the positron in 1932 by Carl Anderson, studying cosmic particles in a cloud chamber. Using the same technique, Anderson found the muon in 1936, a particle about 200 times heavier than the electron, identified later as the second charged lepton.

It is interesting to note that these early experimental steps in particle physics were done with cosmic rays and visual techniques. The basic detector then was the Wilson cloud chamber, containing a supersaturated vapour of water or alcohol, thus in a metastable state. A charged particle traversing the chambers deposits energy by ionisation, condensing the vapour into small liquid droplets materializing its trajectory. The metastable state is obtained through a sudden provoked expansion of the gas in the vessel.

1.2. First contributions in France

In France, initial experimental investigations in particle physics were also carried out with cosmic rays. One of the important results was obtained by Pierre Auger and collaborators and presented by Jean Perrin in the *Comptes rendus de l'Académie des sciences* [1], when they discovered large-distance time correlations between particles arriving on the ground. This was explained [2] by large showers produced by primary cosmic particles interacting in the upper atmosphere and leading to a cascade of secondary interactions producing many final particles.[1]

1.3. Leprince-Ringuet and his group at École polytechnique

Trained by Maurice de Broglie, Louis Leprince-Ringuet created his own laboratory of nuclear physics in 1936 on the former site of École polytechnique in Paris. The research was quickly focussed on the study of cosmic rays, performed on successive installations at high-altitude sites where the flux is higher and the showers less degraded. The first cosmic laboratory was established at L'Argentière-la-Bessée (1000 m), close to Briançon, in 1939, thanks to the proximity of a Péchiney aluminum factory. It is in this laboratory that André Lagarrigue was trained together with many former École polytechnique students. Even more ambitious projects at higher altitudes were carried out under Leprince-Ringuet. These were truly heroic efforts due to hostile surroundings, difficult access and the need to bring in electric power for energizing the electromagnet surrounding the cloud chamber in order to bend the charged particles and measure their momenta. It was the case for the laboratory at Col du Midi above Chamonix (3600 m) completed in 1943. Between 1951 and 1957, Leprince-Ringuet's group, including Lagarrigue, used the existing observatory on top of the Pic du Midi de Bigorre (3000 m) for continuing cosmic ray studies with a magnetic cloud chamber.

It should be pointed out that, unlike Auger, who was interested in the physics of cosmic rays, Leprince-Ringuet and his collaborators were more motivated by the possibility of discovering new particles produced by the interactions of cosmic rays with matter. In that sense, they can be credited for launching in France the field of particle physics. Indeed they made important contributions concerning a new family of hadrons (strongly interacting particles) called strange particles. In particular, they discovered the decay of kaons through the weak interaction producing a muon in the final state (accompanied by an unseen neutrino) [3].

1.4. Early Lagarrigue research work and publications in the Comptes rendus

Born in 1924 in Aurillac in southwestern France, André Lagarrigue entered École polytechnique in 1944 and graduated as an armament corps engineer. Already during his study years, he was attracted by current research in physics and he got involved in the team around Leprince-Ringuet. The latter quickly detected his exceptional potential and soon after convinced him to apply for a discharge from the military and join fundamental research, thus trading weapons for cloud chambers. Lagarrigue then embarked on experiments at L'Argentière-la-Bessée in order to measure the mass of cosmic particles. One can easily monitor his progress through a series of notes to the *Comptes rendus*. The first one [4], in 1947, when he was still an undergraduate, describes the experimental setup as seen in Fig. 1. Comparing the particle momentum obtained from the track bending in the magnetic field to its range as quantified by the different absorber plates allowed the authors to conclude that the penetrating particles had a mass at least 200 times larger than the electron mass. In fact, when

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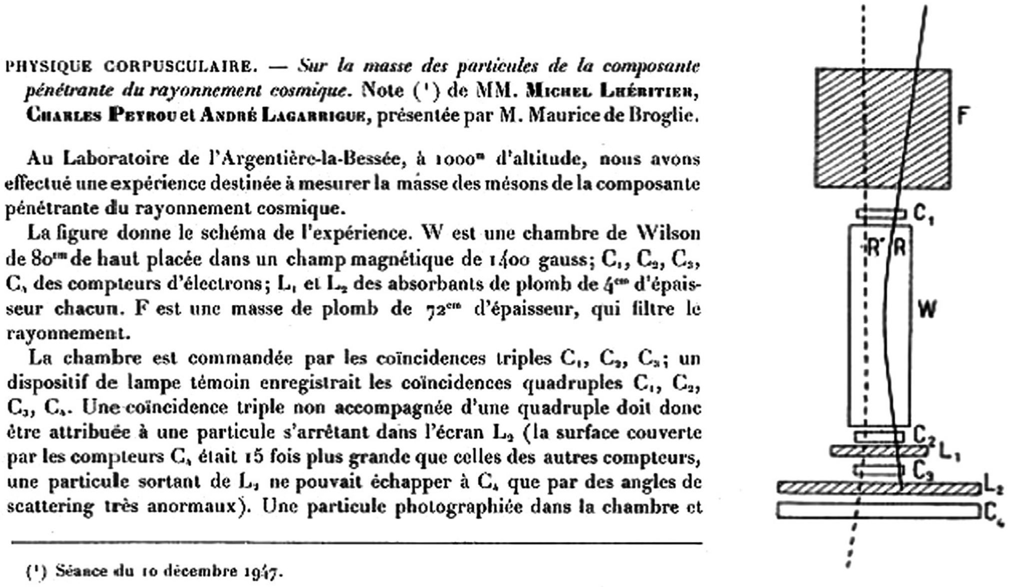
[1] In recognition of this discovery, the modern cosmic international observatory installed in Argentina, and sampling air showers of ultra high energies ($> 10^{18}$ eV) over an area of 3000 km^2, was named after Pierre Auger.



PHYSIQUE CORPUSCULAIRE. — *Sur la masse des particules de la composante pénétrante du rayonnement cosmique.* Note (¹) de MM. **Michel Lhéritier**, **Charles Peyrou** et **André Lagarrigue**, présentée par M. Maurice de Broglie.

Au Laboratoire de l'Argentière-la-Bessée, à 1000^{m} d'altitude, nous avons effectué une expérience destinée à mesurer la masse des mésons de la composante pénétrante du rayonnement cosmique.

La figure donne le schéma de l'expérience. W est une chambre de Wilson de 80^{cm} de haut placée dans un champ magnétique de 1400 gauss; C_1, C_2, C_3, C_4 des compteurs d'électrons; L_1 et L_2 des absorbants de plomb de 4^{cm} d'épaisseur chacun. F est une masse de plomb de 72^{cm} d'épaisseur, qui filtre le rayonnement.

La chambre est commandée par les coïncidences triples C_1, C_2, C_3; un dispositif de lampe témoin enregistrait les coïncidences quadruples C_1, C_2, C_3, C_4. Une coïncidence triple non accompagnée d'une quadruple doit donc être attribuée à une particule s'arrêtant dans l'écran L_2 (la surface couverte par les compteurs C_4 était 15 fois plus grande que celles des autres compteurs, une particule sortant de L_1 ne pouvait échapper à C_4 que par des angles de scattering très anormaux). Une particule photographiée dans la chambre et

(¹) Séance du 10 décembre 1947.

Fig. 1. Left: André Lagarrigue's first publication in the *Comptes rendus* [4] on the study of particles produced by cosmic rays. Right: the experimental setup includes an 80-cm-high cloud chamber W placed in a 0.14-T magnetic field, four ionisation counters (C_{1-4}) between lead absorber plates (L_{1-2}), all behind a massive lead absorber to select incoming penetrating particles. The chamber was triggered by a triple coincidence C_1–C_2–C_3, and a picture of the track was taken together with a flash bulb indicating a quadruple coincidence corresponding to a most penetrating particle.

interpreting the results on the fraction of particles reaching the last counter, there was a preference for a mixture of two particle types with different masses, with respective ratios to the mass of the electron of about 200 and 300.

This finding confirmed a result obtained just before by C. F. Powell and his Manchester group [5] using photographic plates, claiming the discovery of the charged π meson, for which Powell was awarded the 1950 Nobel prize. This meson was the long-sought particle postulated by H. Yukawa to explain through its exchange the short-range strong force between nucleons. So it is nice to see the young Lagarrigue already involved in a frontier problem, sorting out two types of particles close in mass. Indeed, the particle discovered by Anderson in 1936, initially thought to be the Yukawa meson, turned out to be the muon, thus the second-generation lepton and as such insensitive to the strong interaction.

Other notes were presented [6–8] with more and more refined results, confirming the existence of two particle types. In particular, a mass ratio for the muon 212 ± 5 was obtained, consistent with the accurate modern determination 206.768 283(47).

Lagarrigue's doctoral thesis was presented in 1952, following two new publications in the *Comptes rendus* [9,10]. In this work, he studied the decay of the cosmic muon into an electron (or positron, depending on the muon charge) and unseen neutrinos. The shape of the electron energy spectrum had been predicted in 1950 by Louis Michel using a current–current interaction between the two pairs of charged lepton + neutrino. It involved only one parameter ρ, depending on the structure of the currents. It was only five years later that the structure was elucidated as a V–A current (vector and axial-vector) by Lee and Yang, producing a maximum parity violation in the decay, as confirmed immediately in radioactive nuclear β decays by C. S. Wu. This fixes the parameter ρ to the value $\frac{3}{4}$, which is established nowadays with high precision using well-controlled muon samples from accelerators, yielding a value 0.749 79(26). The value obtained by Lagarrigue was much cruder, 0.19 ± 0.13, and four standard deviations away from the true value. In fact, many of the early experiments found low values as well, pointing to some common systematic problems in the method. Nevertheless it was a pioneering effort based on the observation of only 150 events in the difficult experimental conditions prevailing in early cosmic ray research.

2. Research with bubble chambers and accelerators

2.1. From cosmic rays to accelerators at Berkeley

Particle physics took a crucial turn with the availability of high-energy accelerators. The invention of the cyclotron at Berkeley in 1931 by Lawrence and Livingston was followed by increasingly larger instruments housed in huge magnets, culminating in the 184" cyclotron in 1941. After the war, it was transformed into a synchrocyclotron to overcome the relativistic increase of the revolution time at higher energies by a continuous slow-down of the accelerating field frequency. This technique opened the way to larger machines with a fixed orbit radius and a rising magnetic field in order to keep the particles in the ring as their energy increased. In this mode, accelerators with higher energies could be constructed. A new era was born, taking advantage of well-controlled pencil proton beams with high intensity, capable of producing a multitude of new particle types when interacting on a target. The crop started with the neutral pion in 1950.

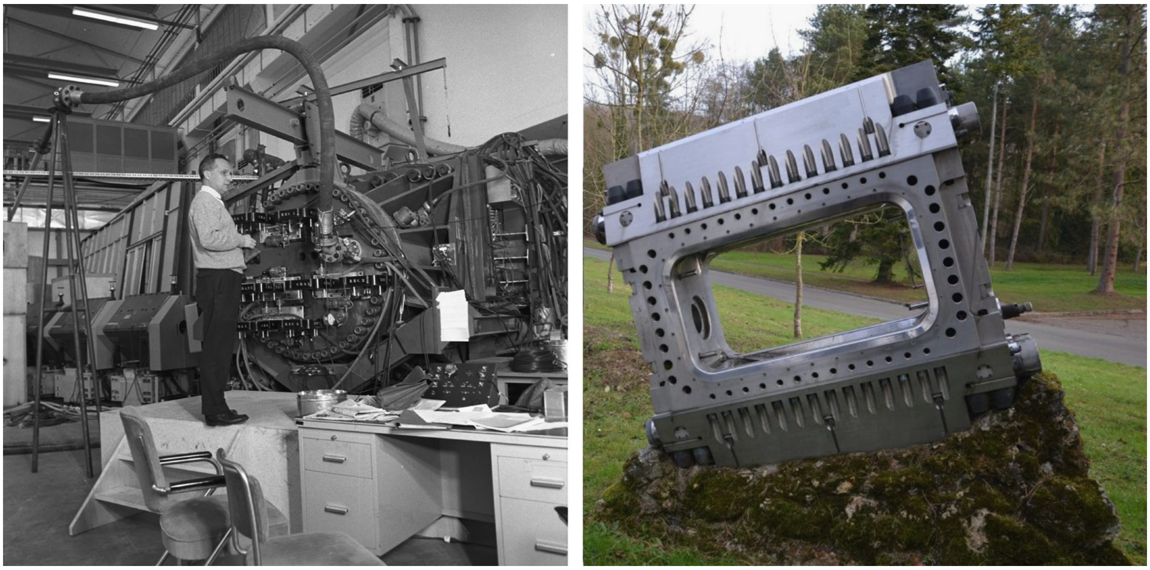


Fig. 2. Left: Lagarrigue standing next to the heavy-liquid BP3 bubble chamber he constructed and moved to CERN (1962). A rich physics programme was carried out, producing important results on hadron resonances and dynamics, as well as on weak decays of neutral kaons. Right: the BP3 chamber body, now a scientific monument standing in front of the building built for hosting Lagarrigue's group in the Laboratoire de l'accélérateur linéaire on the Orsay campus.

In the early fifties, Berkeley was the best place to be. This was clearly understood by Lagarrigue as he moved there in 1954 to immerse himself in this new experimental environment. The timing was excellent: the Bevatron, highest-energy synchrotron in the world just started to operate and a new detector had just been invented by Glaser, the bubble chamber. The principle was similar (actually the reverse) to the condensation droplets in a cloud chamber: charged particles traversing a liquid phase deposit energy by ionisation and create bubbles of gas along their trajectories when the pressure in the liquid is suddenly decreased. The higher density of the liquid meant a larger probability to interact and thus more frequent collisions. The combination of higher fluxes of incident particles and larger interaction rates made possible the collection of large samples of collisions so that the capability to discover and study new particles was strongly enhanced. Lagarrigue realized immediately the potential of accelerators and bubble chambers, a fact that shaped his scientific trajectory for the rest of his life.

2.2. Back to Europe and on the way to CERN

Back in Paris in 1955, Lagarrigue sets the stage for his new endeavours. The situation looked good. First the new 3-GeV synchrotron Saturne had just been decided by the French Atomic Energy Commission (CEA) to be built on the Saclay site. Also early developments of bubble chambers were considered. He was convinced that the time of cloud chambers was over and he began to work on bubble chambers advocating the use of heavy liquids that did not require cryogenic operation as for liquid hydrogen. His vision was clearly to gain experience for designing a chamber as large as technically possible to maximize the interaction rate and follow the tracks in order to identify the nature of the particles. A first chamber of small size (BP1, 4 litres of propane) built at École polytechnique was followed by a second larger one (BP2, 20 litres) moved to a pion beam at the start of Saturne. A big step occurred with the 300-litre BP3 chamber (propane and heavy freon) constructed at Saclay and for which Lagarrigue conceived a very rich physics programme, first with Saturne. This was an audacious project because the chamber operated at 20 bar with liquid propane at 60 °C and good optical properties had to be maintained in order to measure the tracks on film with good precision. However, while being an excellent physicist, Lagarrigue was also a first-class engineer and was able to proceed quickly and successfully in the chamber design.

However, in the meantime, the European Laboratory (CERN) had been created in Geneva and in 1959 the proton synchrotron (PS) started to operate at 27 GeV, one of the two highest accelerators in the world at the time. In his persuasive manner, Lagarrigue was able to negotiate the transfer of BP3 to CERN by convincing the General Director of the CERN, "who showed some worry about the installation of an apparatus built by physicists, filled with 300 litres of a dangerous liquid, and to be placed close to a brand-new world-best accelerator" [11]. The move took place quickly and the chamber was operational in the mid-1960s and ready for experiments spanning a large range of investigations, from hadronic spectroscopy to studies of weak interactions (Fig. 2).

At this time, there was quite a debate about the best liquid to use in a bubble chamber. Many physicists preferred hydrogen, because interactions occur on essentially free protons, unlike for heavy liquids with the complications from nuclear effects. Some others, and Lagarrigue was their champion, advocated that heavy liquids had an advantage because one could see secondary interactions of the produced particles inside the chamber due to the much shorter interaction and radiation lengths of the denser medium. In particular, photons could be identified by their conversion into electron–positron pairs. This advantage turned out to be decisive in some specific experiments, as we shall see later.

The fact that the experiments were carried out at CERN with its unique facilities in Europe attracted many groups of physicists working in collaboration. The data taking was a common task and the large sample of photographs was dispatched to the different collaborating institutes, where they were scanned to select the desired type of collision. The track parameters (3-momenta and particle identification) were measured so that the full interaction process could be reconstructed kinematically. Finally, all the reconstructed data were reassembled and physical analyses could then be performed on the full sample. This new way of working at an international scale meant that the primary results could not be published anymore at the national level, but rather in European-wide scientific journals. This explains the rarity of particle physics contributions in the *Comptes rendus* after the 1950s. One exception, involving Lagarrigue's group at École polytechnique and a group at the university of Milan in 1963, concerns the study of a new hadron resonance at large mass (now called the f_2 meson), which was determined to have a spin equal to 2 [12].

3. Toward the Standard Model: the glorious 1970s

3.1. From hadrons to quarks

The field of particle physics in the early sixties was both very active and yet frustrating. On the one hand, a rich spectrum of new strongly interacting particles (hadrons) had been discovered thanks essentially to a vigorous programme using bubble chambers, and the results on weak-interaction processes were understood within the Fermi theory revisited after the discovery of maximal parity violation resulting from the presence of vector and axial-vector currents of equal strengths. On the other hand, this profusion of hadronic states could hardly be interpreted as being all elementary, yet no theory was able to explain their existence and their properties. Also the three interactions - -strong, electromagnetic, and weak – did not seem to emerge from a more unified framework.

A big step occurred when Gell–Mann realized that the discovered hadrons could be classified in representations (octets, decuplets...) of an SU(3) symmetry of isospin and hypercharge, and that the fundamental triplet representations involved new states he dubbed 'quarks'.[2] In this scheme, mesons emerged as composite quark–antiquark systems, while baryons such as the proton and the neutron were made of three quarks, and antibaryons of three antiquarks.

While Gell–Mann initially considered the quarks to be entities of a more mathematical nature, the evidence for them to be real came from the famous electron-scattering experiments done at the Stanford Linear Accelerator Center (SLAC) [13]. While the proton was already known to have a size at the femtometre level, the SLAC experiments showed that it behaved as a collection of pointlike charges, as quickly understood by Feynman who named them 'partons'. Using neutrons as well as protons, it was observed that the partons had all the properties of the postulated quarks, creating a major breakthrough in the understanding of the strong interaction.

These developments gave André Lagarrigue his first motivation for studying neutrino interactions in a large bubble chamber. Indeed, the strongly bound nucleons could be probed not only with electrons through the electric charge of quarks, but as well with neutrinos through the weak interaction. In fact, the combination of both approaches was going to yield a more solid identification of the constituents as the Gell–Mann quarks.

3.2. Three families of leptons and quarks

The concept and discovery of quarks as pointlike constituents of the hadrons constituted a turning point as they could be considered as elementary, like the electron and the muon. In fact, both the quarks and the leptons were found to have a size smaller than 10^{-3} of the proton's radius. Three types of quarks were identified: u (up), d (down) were found in the proton, the neutron and the light mesons, while strange particles involved in addition the quark s (strange). The four leptons were the electron, the muon, and their respective neutrinos. This asymmetry was awkward and led S. Glashow, J. Iliopoulos, and L. Maiani to postulate the existence of a fourth quark to restore a welcome quark–lepton symmetry, which turned out to be an essential theoretical ingredient [14]. The 1970s were decisive years with respect to this problem. First the existence of this new quark c (charm) was proven true through experiments with electrons–positrons at SLAC [15] and protons at Brookhaven [16] in 1974. Then the same experiment at SLAC also discovered [17] a third charged lepton (τ) in 1976. Finally, a fifth quark b (bottom) was found at Fermilab [18] in 1977. Furthermore, the observed properties of these new particles required the presence of a new neutrino associated with the τ lepton and a sixth quark t (top), both established experimentally in later years.

The resulting picture of the elementary constituents of matter appeared as formed of three families, each composed of a charged lepton, a neutrino, and a quark doublet: hence, the first $(\mathrm{e}, \nu_{\mathrm{e}}, \mathrm{u}, \mathrm{d})$, second $(\mu, \nu_{\mu}, \mathrm{c}, \mathrm{s})$, and third $(\tau, \nu_{\tau}, \mathrm{t}, \mathrm{b})$ families. Was it the end of the story? For the moment and up to now, yes, as the precision experiments performed on the LEP collider at CERN have restricted to just three the number of lepton–quark families. The profound origin of this pattern remains for the moment a mystery.

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[2] The quarks were also independently proposed by G. Zweig.

3.3. The Glashow–Weinberg–Salam model of electroweak interactions: weak neutral currents?

Just as the spectrum of elementary particles was unravelled in the 1970s, the fundamental interactions were also brought to a new level of understanding through the framework of the so-called gauge symmetries. These symmetries of a geometric nature allowed one to derive the theoretical form of the interactions, each generated from a specific symmetry group. As gauge invariance operates in electromagnetism, the quantum theory of electromagnetic interactions (QED) is a gauge theory under the U(1) group, with the photon being a gauge boson propagating the force between electric charges. Similarly, the known weak interaction could be described by the exchange of a charged W boson, as the interaction involves a transition between charged and neutral leptons (neutrinos). This necessitates a gauge group SU(2) to account for the doublet structure. The charged weak interaction is also at work in a transition between members of quark doublets. Finally, the strong interaction between quarks can also be described by another gauge theory, this time based on the SU(3) group with eight gauge bosons, the gluons g.

Since all three interactions are described in a similar way, a promising approach is to try to unify them under the same type of theory with a larger symmetry group. But this would imply the same interaction strength, which is far for being true for the observed ones. At femtometre distances, weak and electromagnetic forces differ by orders of magnitude, so it looks difficult to unify them. However, this can be overcome by postulating a mass in the order of 100 GeV for the W boson, thus reducing the range of the weak interaction, compared to the infinite range of QED. The theory proposed by S. Glashow, S. Weinberg, and A. Salam [19] brings together electromagnetic and weak interactions within the same framework with two gauge groups: a complete weak-isospin symmetry SU(2) with a triplet of W gauge bosons (W^+, W^0, W^-) and a new weak-hypercharge U(1) symmetry with a singlet neutral B gauge boson. In this way, the charged weak interaction remains unchanged, while the neutral weak interaction and the hypercharge U(1) mix, leading to physical interactions: QED with the massless photon and a neutral part of the weak interaction hitherto unknown, mediated by a new massive Z^0 boson. This scheme provides a relation between the W and Z masses, through the mixing angle θ_W.

Confirming experimentally the Glashow–Weinberg–Salam model was clearly a top priority around 1970. A first crucial step was to discover the neutral weak interaction described by the so-called neutral currents, analogous to the electromagnetic currents.

4. Lagarrigue, Gargamelle, and the neutral current story

4.1. A planned programme for neutrino interactions

After the hadron studies with BP3, André Lagarrigue shifted his interest to physics with neutrino beams. His motivation was at least threefold. First, as we mentioned above, the fascinating results at SLAC from electron scattering called for similar studies with neutrinos to confirm them and complete the information on the properties of the quarks. Second, there was a strong desire to search for the neutral currents predicted by the electroweak Standard Model. For this neutrinos are ideally suited: since they have no electric charge, electromagnetic interactions are turned off when they scatter on a target. Thus, if a neutrino interacts through neutral currents, it will remain in the final state, corresponding to the exchange of a neutral Z boson. On the contrary if a muon neutrino scatters under the usual charged weak interaction, it will be transformed into a charged muon, which can be easily detectable. Thus, the idea was simple: a charged-current event is signed by a muon track in the detector, besides the produced hadrons resulting from the excitation of the target nucleon, while no such muon should be observed in a neutral-current event, since the scattered neutrino will leave no visible track. Third, neutrinos interact very weakly with matter, so a large mass detector is needed in order to get a reasonable event yield. With the trend of larger and larger bubble chambers in which he took a major part, Lagarrigue knew which way to go. The solution was to build a large heavy liquid bubble chamber, much larger than the previous ones to get the mass, with the bonus that muons could be much better identified due to their long tracks, whereas produced hadrons in the same event would interact in the large volume due to their strongly interacting nature.

First ideas outlining this programme were born in 1963 at a conference in Sienna. A first realistic proposal to build a huge bubble chamber was presented the following year, just at the time when Lagarrigue was offered a professorial chair at Orsay, where he moved together with a good part of his group. After securing a design and construction phase at CEA-Saclay, it took 18 months to convince CERN to have the future chamber installed in a neutrino beam, thus putting Lagarrigue's visionary project on solid grounds.

At an international colloquium on bubble chambers held at Heidelberg in 1967, Lagarrigue presented his views on the future of neutrino physics with large chambers. Quite naturally, he gave the search for neutral currents a high priority and already discussed the expected backgrounds that could fake such processes: "The lack of neutral currents is one of the major issues of the weak interaction physics with neutrinos" [20].

4.2. The large Gargamelle bubble chamber

Despite the higher neutrino flux achieved at CERN, the need for a very massive detector was mandatory to obtain a large sample of neutrino interactions. In fact, it required a huge extrapolation from the 300-litre BP3 chamber. The new vessel,

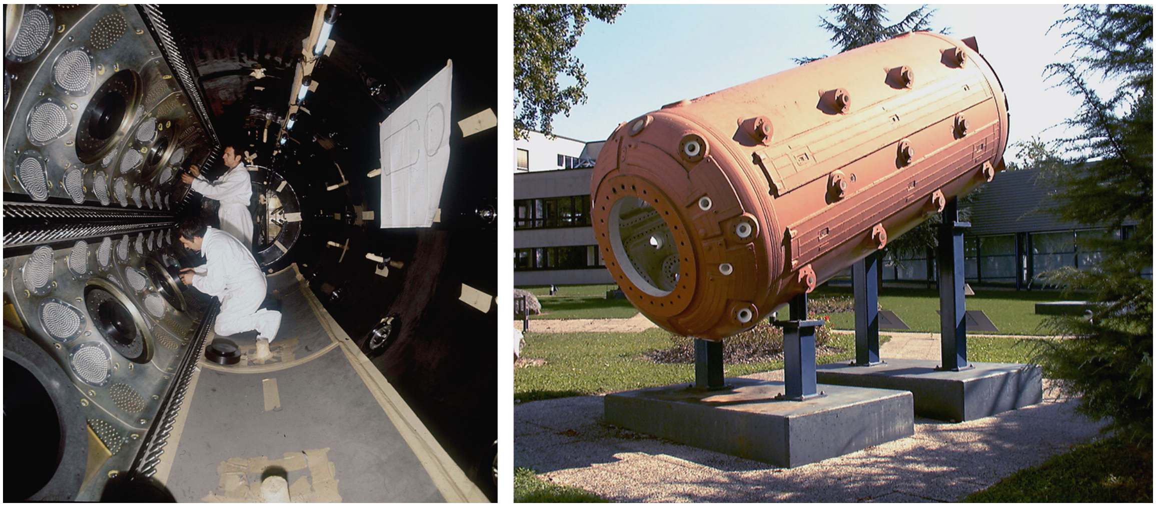

Fig. 3. Left: the inside of Gargamelle during the final stages of its installation in 1970. Technicians are mounting the optical flanges for the cameras on the left side, while the openings on the right are for the flashlights. Right: the Gargamelle chamber body standing for display on the CERN grounds as part of the permanent Microcosm exhibit.

appropriately named Gargamelle,[3] had a cylindrical shape with a diameter of 1.9 m and a length of 4.8 m, thus a volume 50 times larger than that of BP3, and filled with 12 m^3 of liquid freon CF_3Br. The chamber body was surrounded by a large magnet delivering a field of 2 T (see Fig. 3).

Building a bubble chamber of this size required solving many problems, well analyzed by Lagarrigue in a paper entitled *Les grandes chambres à bulles* ("Large bubble chambers") [21]: design of the large magnet, a system to uniformly illuminate the bubbles on the tracks, a complex optical arrangement of eight large-angle cameras viewing the whole volume, all bringing a host of mechanical problems. Nevertheless, he remained optimistic: "The project is being realized by a team who has built the chambers of the previous generation. One can hope that, even if the commissioning takes more time, the outcome should be as successful as with the present chambers."

Indeed, the construction was achieved successfully, the installation at CERN started in July 1970 and the first pictures of cosmic rays were taken five months later: Gargamelle was ready for its neutrino programme. In the meantime, a large team with physicists from France, Italy, Germany, UK, Belgium, and CERN was assembled to scan the forthcoming pictures, measure the particle tracks, identify the events, and carry on the physical analyses. However, the need for a high neutrino flux required that the proton synchrotron intensity be devoted fully to the neutrino beamline. Lagarrigue went to great efforts to convince the CERN management to allocate the needed beamtime to the Gargamelle experiment in the face of other unhappy users competing for protons. The results to come showed that the decision was very well justified.

4.3. The discovery of neutral currents

Let us recall how neutrinos interact with matter, i.e. nucleons and electrons. In the processes mediated by charged currents and exchange of a $W^\pm$ boson, the incoming neutrino turns into the corresponding charged lepton. In a neutrino (anti-neutrino) beam, obtained from the decay of charged pions π^+ (π^-), one finds essentially muon neutrinos ν_μ ($\overline{\nu_\mu}$). The interaction processes for neutrinos (for anti-neutrinos, the first lepton in the final state should be turned into its antiparticle) are thus (N stands for nucleon, i.e. either proton or neutron):

$$\nu_\mu\ e^- \rightarrow \mu^-\ \nu_e \qquad \text{(leptonic charged currents)} \tag{1}$$

$$\nu_\mu\ N \rightarrow \mu^-\ \text{hadrons} \qquad \text{(leptonic and hadronic charged currents)} \tag{2}$$

In the corresponding processes with neutral currents, the outgoing lepton is identical to the incoming neutrino and the exchanged boson is Z^0:

$$\nu_\mu\ e^- \rightarrow \nu_\mu\ e^- \qquad \text{(leptonic neutral currents)} \tag{3}$$

$$\nu_\mu\ N \rightarrow \nu_\mu\ \text{hadrons} \qquad \text{(leptonic and hadronic neutral currents)} \tag{4}$$

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[3] Gargamelle is the mother of the Gargantua giant in the famous book by François Rabelais. Besides referring to her unusually large size, the chosen name includes 'gamelle' which is a familiar French name for a container, thus quite suitable for a bubble chamber!

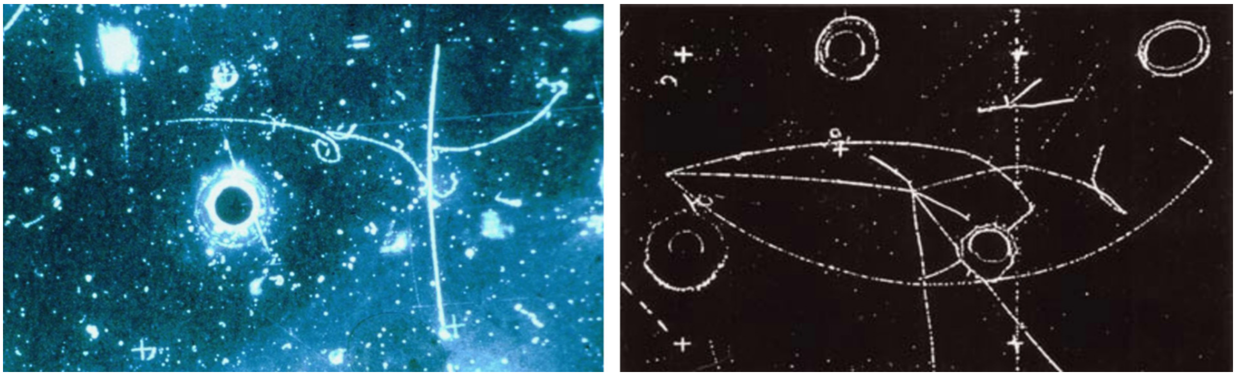

Fig. 4. Left: the first leptonic neutral-current event found with Gargamelle: a single-electron track is observed with a typical behaviour in matter (bremsstrahlung and photon conversions into electron–positron pairs). Right: a neutral-current event producing hadrons in the final state, identified by a characteristic scattering pattern, and without any long muon track. The incoming neutrino beam comes from the left.

Initially, the processes with charged currents were found as expected, characterized by their long muon tracks. This sample of events such as (2) had a rate and properties consistent with the description of the nucleon in terms of pointlike constituents, thus confirming the results and the interpretation of the SLAC electron scattering experiments with further information about the charge of the constituents.[4] Thus the quark structure of the nucleon was fully established with quarks u and d of respective charges $+\frac{2}{3}$ and $-\frac{1}{3}$ in units of the elementary electric charge.

With the accumulation of more data, the neutral current search was actively pursued. The first golden event, found in December 1972 in the antineutrino sample, was of the type (3), appearing as a single track emitted along the neutrino beam direction and identified as an electron because of its electromagnetic activity (bremsstrahlung and pair conversions) with a short path dictated by the small radiation length (11 cm) of liquid freon (Fig. 4). Although the estimated background for this topology is negligible, one can be very unlucky with only one event, so the second event of this type, found one year later, followed by a third one with the full statistics of one-million pictures, was a decisive proof.

For the interactions with produced hadrons, more and more candidates for events of the type (4) were found, creating a lot of excitement in the Gargamelle collaboration. However, there was a priori a serious problem to consider. The neutral current topology, i.e. an invisible incoming particle producing a system of hadrons without muon, could be mimicked by neutrons interacting in the chamber volume. These neutrons could be produced by neutrino interactions in the shielding upstream. It was a real achievement of the physicists to understand quantitatively this type of background and to show that the large majority of the candidates could only be explained by neutral currents. A typical event is shown in Fig. 4. The two pictures (leptonic and hadronic events) show convincingly the power of a heavy liquid bubble chamber to select and identify these neutral-current events, validating in a spectacular way the intuition and the scientific vision of André Lagarrigue.

The discovery was disclosed, together with the first leptonic event at conferences in the summer of 1973, and two seminal papers were published in quick succession on the electron event [22] and the semileptonic candidates [23]. The results were received by the physics community with a range of feelings, from great enthusiasm by most to incredulity by some, especially those who were running a competing experiment in the USA and failed to find a signal. After further more conclusive studies of the neutron background and the second electron event, the issue was successfully settled by the Gargamelle collaboration in early 1974 with a definitive paper [24]. Furthermore, the existence of neutral currents was finally confirmed by two experiments at Fermilab using electronic detectors instead of visual devices.

It should be mentioned at this point that, in addition to his leadership of the Gargamelle programme and the critical role he played in making the neutral-current discovery convincing and reliable, André Lagarrigue had many other contemporary duties. He was very involved in teaching and he was asked to chair a committee appointed by the Minister of Education in order to reform the way physics was being taught at high-school level. Also he was the head of a large laboratory on the Orsay campus, the Laboratoire de l'accélérateur linéaire, of which he organized the three-prong scientific missions with local electron–positron colliders and experiments, bubble chamber activities, and the preparation of the programme with the super-synchrotron SPS under construction at CERN. In the context of these heavy responsibilities, the fight to have the Gargamelle discovery recognized must have been a truly exhausting task for him in the years 1973–1974. On 14 January 1975, after delivering his morning lecture to pre-med students, he suffered a stroke and died shortly after. A brilliant scientific career came suddenly to an end.

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[4] The electron scattering cross section depends on the sum of the square of the parton charges, whereas neutrino scattering through charged currents is sensitive to the parton charge.

5. Impact of the discovery and confirmation of the full Standard Model

5.1. Weak electromagnetic interference with particles and atoms

The discovery of weak neutral currents in Gargamelle ranks certainly as one of the most important milestones in particle physics. The establishment of the neutral component of the weak interaction validated its SU(2) structure with a triplet of W gauge bosons. Thus it was the first crucial step in the confirmation of the electroweak Standard Model. In addition, the relative rate of charged and neutral currents in neutrino interactions provided the first indication of the level of mixing between the W^0 and B gauge bosons into the physical Z^0 and γ states. It is in this sector that further investigations were necessary in order to test quantitatively the $SU(2) \otimes U(1)$ gauge symmetry.

To achieve this goal, it was necessary to consider processes involving neutral currents with charged leptons: for example, the equivalent of reaction (4) with ν_μ replaced by an electron. Such a process is dominated at small values of the squared 4-momentum transfer (q^2) by the electromagnetic interaction mediated by photon exchange, but a weak interaction is also possible with Z^0 exchange. Thus, the two amplitudes are expected to interfere. This interference term, linearly increasing with q^2 with respect to the main electromagnetic amplitude, was indeed going to be measured in three very different experimental conditions. First, an inelastic electron scattering experiment at SLAC measured a parity-violating asymmetry using a polarized beam [25] at $q^2 \sim 1$ GeV^2. Second, the same effect was found in atomic transitions at a much reduced scale ($q^2 \sim 1$ MeV^2) in a beautifully designed optical experiment at École normale supérieure in Paris [26]. Third, measurements of electron–positron annihilation into all types of fermion-antifermion pairs, leptons as well as quarks, were performed at the highest-energy colliders at DESY (Hamburg) and SLAC, and established the universality of the neutral couplings exactly as predicted by the Standard Model [27].

5.2. Discovery of the weak bosons W and Z

Establishing the existence of weak neutral currents, their relative occurrence compared to charge currents, the interference between weak and electromagnetic processes with neutral exchange was a tremendous achievement. Yet the physical weak bosons $W^\pm$ and Z^0 were still elusive, but for a good reason: from the above measurements, the mass scale for the bosons could be estimated to be around 100 GeV, well above the accessible range with the accelerators existing at the time. Even though the highest energy synchrotrons had proton beam energies of 400 GeV (Fermilab) and 300 GeV (SPS at CERN), the maximum mass they could achieve in a standard collision with a proton target was less than 30 GeV. This impossibility was circumvented through an ambitious proposal made by Carlo Rubbia to transform the SPS into a proton–antiproton storage ring, hence providing access to centre-of-mass energies well above 100 GeV.

However, the task was enormous, as it was necessary to produce enough antiprotons and have their phase space compressed so as to achieve enough luminosity to drive the rate of collisions between the counter-rotating proton and antiproton bunches in the collider ring. This challenge was solved by Van der Meer using the ingenious technique called stochastic cooling. Two large experiments (UA1 led by Rubbia, UA2 by Darriulat) were built to study the collisions and identify the produced weak bosons through measurements of their decay products. The discoveries in short sequence of the W [28,29] and the Z [30,31] with masses consistent with expectations were great news and another big step.

5.3. Precision tests with LEP

Even before the discovery of the bosons, there was enough confidence in the Standard Model, so that Europe and CERN decided to build a very large electron–positron collider (LEP) to produce generous samples of Z bosons in a first phase (∼ 100 GeV) and W^+W^- pairs in a second step (∼ 200 GeV). The physics programme of LEP from 1989 to 2000 was deployed through four detectors exploited by worldwide collaborations, establishing CERN as the main laboratory in the world for particle physics, still run by Europe, but open to all countries. As a result, the masses of the bosons could be measured with extreme accuracy (91 187.6 MeV with an uncertainty of only 2.1 MeV for the Z boson) and Z decays provided large samples of all types of fermions. Most precise determinations of all weak couplings were performed. In addition, detailed studies of the strong interactions at the quark and gluon level confirmed beautifully the quantum chromodynamics (QCD) gauge theory.

There was in fact a strong incentive for performing these exceedingly precise measurements, much beyond a pure metrological interest. The electroweak Standard Model is a well constrained theory depending on only a few parameters. Once these are known accurately, consistency tests could be performed. However, some parameters were still out of reach: in particular the mass of the sixth quark (top) was too large to be produced with LEP. However, this mass entered in higher-order calculations of some observables, so measuring precisely their value and comparing to the theory yielded precious information about the top quark mass. A great success of this investigation came from the direct observation of the top quark at the upgraded Fermilab synchrotron (TeVatron) which fell in exactly the window predicted by LEP. A review of the LEP results appeared in the *Comptes rendus* [32].

5.4. The crowning of the Standard Model and the discovery of the Higgs boson

When the LEP exploitation was terminated in 2000 so that its tunnel would be free to install the Large Hadron Collider (LHC), the Standard Model was thoroughly and successfully validated. But, in fact, one aspect was still only indirectly checked: the validity of the gauge symmetry breaking, proposed independently by R. Brout-F. Englert and P. Higgs. Their approach solved a basic problem of the theory: gauge symmetry can only be satisfied by massless bosons, such as in QED with the photon, but it cannot accommodate the very massive weak bosons. The BEH mechanism involves new scalar fields that are absorbed by the extra field components needed to describe massive bosons, only one of which subsists as a physical field and should correspond to a new scalar (spin 0) boson, called the Higgs boson.

Many efforts were deployed by LEP experiments to search for this boson, but no signal was found up to a mass of 115 GeV, limited by the maximum attainable beam energy. This was very close to the expectation from the confrontation of the precision electroweak LEP measurements and the theory, which provided a mass of order 100 GeV within a 25% margin. Finding the Higgs boson was the primary goal of the LHC collider, which was fulfilled in July 2012 by the two large-purpose detectors, ATLAS [33] and CMS [34]: the Higgs boson was indeed there at 125 GeV, in the range favoured by precision electroweak measurements. Also the measured properties of the new boson behaved as expected, in particular the fact that its coupling with fermions is not universal, but rather proportional to the fermion mass. This fantastic achievement was the final crowning of the Standard Model, with the last missing piece falling into the right place.

5.5. Perspectives

Started with the discovery of the neutral currents, the experimental trail leading to the finding of the Higgs boson changed the status of the Standard Model, indeed the genuine theory of the fundamental interactions rather than just a model. At this point, one could be tempted to declare particle physics as a closed subject. But this would imply the absence of any new physics phenomena between the electroweak energy scale of 100 GeV and the Planck scale of 10^{19} GeV, where relativistic quantum mechanics meets gravity. However, this would be at best a naive and short-sighted conclusion, but most probably a mistake.

There are several theoretical arguments against the Standard Model as the final theory. Also some experimental facts do not receive an explanation in this framework. Let us just mention at this point the observation of a large amount of dark matter in the universe for which no astrophysical objects have been found and for which no particle candidate exists in the Standard Model. As always in physics, the quest will go on and eventually the standard theory will have to be modified to explain these shortcomings.

6. Conclusions

In this article, we have seen the role of André Lagarrigue in the development of modern particle physics. His early career is well documented in the *Comptes rendus*, with several presentations describing his progress in experimentation with cosmic rays. These pioneering experiments were certainly modest, but raising physics questions at the forefront of the field, and they were an ideal place to learn and become a good experimentalist. After a period in Berkeley, Lagarrigue realized the opportunities offered by the high-energy particle accelerators and the newly invented bubble chambers. From there on, his scientific path was set with the development of larger and larger chambers, each time contributing to the progress of the field, and culminating with the construction of Gargamelle, the leadership of the international collaboration, and the discovery of weak neutral currents. It is amazing to see how this discovery set the stage for all the following developments, defining the strategy for the critical steps that led to the confirmation of the Standard Model of particle physics. As the first link in this chain of capital measurements, the discovery of neutral currents was well worth a Nobel prize for André Lagarrigue, if not for his untimely tragic death.

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