Particles of man (part III)

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Abstract This article is the third of a three-part series that briefly retraces the milestones in the development of particle physics, which led to what we believe is a consolidated framework, manufactured by man to explain what he himself observes, in his role as part of nature. See Part I in *Lettera Matematica International Edition*, *Lett Mat Int* (2013) 1:145–154 (DOI [10.1007/s40329-013-0025-x](https://doi.org/10.1007/s40329-013-0025-x)) and Part II in *Lettera Matematica International Edition*, *Lett Mat Int* (2013) 1:199–208 (DOI [10.1007/s40329-013-0034-4](https://doi.org/10.1007/s40329-013-0034-4)).

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Foreword by Pietro Nastasi

The author of this article, part III of a three-part history of modern physics, passed away on the evening of 16 February 2014. He had not yet seen his 58th birthday, which would have been on 4 April. We, his friends and colleagues, knew that there was a possibility of a tragic ending, and yet we could not bring ourselves to accept such a terrible thing.

We will miss his sweet smile, his calm, ever lucid analyses irrespective of whether the talk was on history, science or economics, his capacity to carry on with his work in conditions that were so difficult, and in spite of not having achieved the recognition he deserved. A recognition

that would have crowned his extraordinary talent and brilliance in teaching, which was manifest during the many seminars he held.

Giulio Maltese received his degree in physics in Rome in 1981 and for some years worked in climatology before joining the IBM Research Centre in Rome, where he devoted his energies to problems of automatic voice recognition using statistical methods. However, the area in which his contributions shone the most—and in which they are also more numerous—is that of the history and popularisation of modern and contemporary physics. We need only cite the two works published by Zanichelli: *Enrico Fermi in America* (2003) and *Il Papa e l'Inquisitore. Enrico Fermi, Ettore Majorana, Via Panisperna* (2010), the first of which was awarded the 2004 ‘Giovanni Maria Pace’ Prize for popular science. Both of these are fascinating and well-written accounts of the intense, dramatic years that marked a turning point in the history of modern science.

11 The Standard Model and the search for the Higgs boson¹

The Standard Model (SM) accounts for a large number of phenomena and includes all the laws governing the interactions we know, with the sole exception of gravity [2, 7]. The particles of matter it deals with can be divided in two large families: quarks and leptons [8] (Table 1).

The SM consists of two theories: the electroweak theory and QCD. The enormous success in the understanding of

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¹ The present article was submitted before the experiments carried out at the CERN in Geneva confirmed the existence of the Higgs boson, predicted theoretically by the physicist Peter Higgs, Nobel Prize for Physics in 2013 together with François Englert.

Table 1 Families of fundamental fermions in the SM, which form the ultimate constituents of matter

Fermions			
Quarks	(u, d)	(c, s)	(t, b)
Leptons	(ν_e, e)	(ν_μ, μ)	(ν_τ, τ)
	First family	Second family	Third family

Quarks u, c, t have charge $2/3$ (measured in e units, the proton charge); quarks d, s, b have charge $-1/3$. The baryon number of quarks (antiquarks) is $1/3$ (resp. $-1/3$), while it equals 1 for protons and neutrons, and -1 for the respective antiparticles. Their masses (in MeV/c^2) are estimated to be around 3.5–6 (d), 1.5–3.3 (u), 70–130 (s), 1160–1340 (c), ~ 4200 (b), ~ 170000 (t). Quarks and leptons all have spin $1/2$. The largest chunk of existing nuclear matter is made by quarks of type u and d . The proton is formed by a triple uud with electric charge $2/3 + 2/3 - 1/3 = 1$; the neutron consists of a triple ddu of total charge $-1/3 - 1/3 + 2/3 = 0$

Table 2 Bosons carrying interactions, and Higgs boson

Bosons	
Fundamental interactions	Mediators
Strong	8 gluons
Electromagnetic	γ
Weak	W^+, W^-, Z^0
Gravitational	Graviton
Higgs Boson	H^0

Gluons and bosons that mediate the weak force carry their respective charges, and so can interact with one another. The carrier of the gravitational field, called graviton, is believed to have spin 2 and zero mass, since the range of the interaction is infinite

interactions that unfolded from the second half of the twentieth century and has continued to our day is based on the deep relationship between interactions and symmetries, thought of as laws that transform particles into other particles. The SM for the strong and electroweak interactions relies on the symmetry $\text{SU}(3)_c \times (\text{SU}(2)_w \times \text{U}(1)_{Y_w})$ involving special unitary groups. We believe that the early history of the universe witnessed a very short period of time immediately after the Big Bang, lasting around 10^{-11} s, during which quarks, leptons and the gauge bosons of the primeval plasma had zero mass and interacted under the laws of the gauge symmetry just mentioned. Below the energy level of one hundred GeV the symmetry of the electroweak force broke spontaneously—we believe by the “Higgs mechanism”—giving rise to the massive bosons W^+, W^-, Z^0 . During this phase transition of sorts, below 100 GeV, we passed to the universe as we know it today, that is, from a $\text{SU}(2)_w \times \text{U}(1)_{Y_w}$ -symmetry to $\text{U}(1)_{em}$, the symmetry of the electromagnetic interaction: its gauge boson is the photon, which has zero mass just like the gluons that carry the strong force (Table 2).

We remarked earlier (§10) that the key to understanding the Higgs mechanism lies in the fact that the expected value in vacuum of the Higgs field, in passing from the convex potential to the ‘sombrero’ potential, jumps from 0 to v . If we want to understand how this happened while the universe was cooling down after the Big Bang, we have to keep in mind that the Higgs potential V_H depends on the temperature. Today this temperature is very low (2.7 K, the cosmic background radiation) but in the primordial universe the Higgs potential depended on the temperature rather strongly. The electroweak phase transition happened at a temperature of around 100 GeV precisely because for that particular value the sign of the parameter μ^2 is believed to have changed from plus to minus, and the expected value of the Higgs field in vacuum passed from 0 to v . At this stage the gauge bosons of the broken electroweak symmetry acquired mass, and so did quarks and leptons; their masses depended on the intensity of the interaction with the Higgs field. Alas, the SM gives us no indication about the exact value of these constants: we can recover them only *after* having measured the masses of fermions experimentally.

And what about the Higgs boson? The experiments performed to understand its properties began in the LEP (Large Electron Positron Collider) at the CERN in Geneva, which was active from 1989 to 2000 [10]. Using the LEP it was possible to estimate a lower limit for the mass equal to $114.4 \text{ GeV}/c^2$. The study resumed with the newly constructed and high-powered LHC (*Large Hadron Collider*), a hadron–hadron collider believed to reach energies of 14 TeV. Recent observations at the LHC (July 2012) provided evidence of the existence of a particle with features similar to those that the Higgs boson should have, and a mass of about $125 \text{ GeV}/c^2$ [4]. More experimental evidence is now needed to confirm these first clues.

12 The elusive neutrino

It was Bruno Pontecorvo who, in 1958, first noticed that there are no reasons why neutrinos must be massless. If neutrinos do have a mass, no matter how tiny, and their mutual interactions don’t preserve lepton numbers, then they might *oscillate*. In other words the neutrinos and antineutrinos created in weak decays might be described by the mixture of states of neutrinos with a certain mass. Back in 1957 [3] only one kind of neutrinos were known, so Pontecorvo’s initial expectation referred to the possible transition from neutrino to antineutrino. In 1967, after the discovery of the muon neutrino ν_μ (1962), Pontecorvo extended his initial idea. Let’s consider, say, the neutrinos produced by the sun’s nuclear reactions: they are all electronic neutrinos ν_e . If we assume the spontaneous

transformation $\nu_e \rightarrow \nu_\mu$ is possible, the flow of solar electronic neutrinos reaching the earth should be more or less half of what the models forecast. The first, pioneering, experiment in this direction was made in 1969–1970 by Raymond Davis Jr. (Nobel Prize in 2002), and supported Pontecorvo's hypothesis. However, more than 30 years would have to pass before the oscillations of the neutrino were finally confirmed [1, 6]. These oscillations imply that lepton numbers with “flavour” L_e, L_μ, L_τ aren't preserved, and the difference of the squares of the masses of two neutrinos with distinct flavour is non-zero. Therefore at least one neutrino must possess a mass, although the oscillations alone don't determine its value.

The existence of oscillations means that neutrinos have a mass and that they are mixtures of eigenstates, as we saw when discussing mixtures of quarks. Actually, it's not even correct to talk about the mass of ν_e, ν_μ, ν_τ . These are the “eigenstates with weak flavour”, i.e. those one should consider during decay. In vacuum, instead, one must look at mass eigenstates, say ν_1, ν_2, ν_3 . The assumption one makes is that flavour eigenstates are linear combinations of mass eigenstates, and the coefficients form a 3×3 matrix, as for quarks.

The problem of the neutrino mass is crucial in particle physics. If non-zero, the neutrino travels at a speed lower than light and its spin won't be parallel to the momentum (§8). If so, the lepton number is not conserved and there isn't any preserved quantum number to distinguish the neutrino from the antineutrino. The neutrino could coincide with its antiparticle: $\nu \equiv \bar{\nu}$, a possibility first envisioned by Ettore Majorana in 1937, 1 year before his still mysterious disappearance. For this reason we speak about the *Majorana neutrino*, as opposed to the Dirac neutrino whose lepton number is preserved. How does one tell whether a neutrino is Dirac or Majorana? The best way comes from the so-called double beta decay, a rare nuclear process studied for the first time in 1935 by

Maria Goeppert Mayer, to date the only woman after Maria Curie to win the Nobel Prize for Physics (1963). During the double beta decay two neutrons simultaneously transform into protons according to the rule $2n \rightarrow 2p + 2e + 2\nu_e$. But if the neutrino and its antiparticle (Majorana neutrino) were the same object, the process could also be $2n \rightarrow 2p + 2e$ (the antineutrino generated in the first step is absorbed in the second step): this is the double beta decay without neutrinos. What happens in reality? Today we still have no evidence of the existence of Majorana neutrinos. The neutrino-antineutrino distinction remains a crucial step in every explanation proposed in order to give the neutrino a mass.

13 Is there physics beyond the Standard Model? Open problems

The conjectures of the SM have been verified with extreme precision, and we believe that up to energy levels of a few hundreds GeV it provides a very good description of the phenomena observed, see Table 3 (even in the absence of conclusive evidence of the existence of an essential part of the theory such as the Higgs boson). There are nevertheless a number of reasons to think that the SM is incomplete, and that it represents a truthful systematization only at relatively low energies.

For starters, the SM contains many parameters whose numerical values can't be justified theoretically: the masses of leptons, quarks and gauge bosons, the mass of the Higgs boson, the coupling constants, the entries of the CKM matrix.

The SM is structured in three families of quarks and leptons (Table 1). Each family has two quarks and two leptons, but there isn't an honest explanation of why this is so (why only three families for instance). Only the electron, the proton and the neutron (hence quarks u and d)

Table 3 Comparison between the main features of the fundamental interactions (at low energies)

Interactions						
Force	Intensity (adimensional constant)	Range (cm)	Target particles	Exchanged particles (bosons)	Mass of exchanged bosons	Spin ^{Parity} of exchanged bosons
Strong	0.1 (short ranges) 1 (large ranges)	10^{-13}	Quarks Gluons	8 gluons	0	1^-
Electromagnetic	1/137	∞	Electrically charged particles	Photon	0	1^-
Weak	1.027×10^{-5}	$<10^{-15}$	Leptons, quarks	W^+, W^-, Z^0	80.2, 91.2 GeV/ c^2	$1^+, 1^-$
Gravitational	5.9×10^{-39}	∞	All	Graviton	0	2^+

The conservation laws of energy, linear momentum and angular momentum apply to all forces. In the first three cases the charge (Q), the colour, the baryon number (B) and the three lepton numbers (L_e, L_μ, L_τ) are preserved as well. P and C are conserved in all processes governed by electromagnetic and strong forces, but not under weak interactions

enter directly in the composition of stable matter on the earth. Photons are created during transitions between states. At the moment we still can't explain why there are so many particles compared to the few that constitute stable matter.

We don't know the exact origin of quark mixtures, as described by the CKM matrix. The matrix has four independent parameters, one of which is related to *Charge Parity* (CP) violation. This symmetry breaking, in turn, has to do with the asymmetry matter–antimatter. If CP were an accurate symmetry the laws of nature would be the same for matter and antimatter. Yet we have known since 1964 that certain sporadic processes involving weak interactions violate CP [5]. At the end of the 1960s it was discovered that CP violation is the key condition for generating matter as we know it: the universe seems to be made of matter, virtually without antimatter. The imbalance between matter and antimatter couldn't have emerged without some sort of violation of CP during the initial stages of the universe. This forces an asymmetry particle–antiparticle. Now, despite the fact that SM agrees by and large with accepted experiments, in order to explain the matter–antimatter asymmetry there must exist further sources of CP violation besides those we know today.

Regarding this point, a good candidate is the so-called lepton mixing discussed earlier. This phenomenon dictates the existence of a mixing matrix similar to the CKM matrix. For this matrix, too, CP could be violated, provided the phase doesn't vanish. The extent to which CP can be violated depends on another parameter of the matrix that we still have to estimate. The measurements in question are incredibly difficult, yet very important. The only known source of CP violation (in quark mixtures) isn't good enough to justify the observations. A violation of CP in the lepton sector might account for the asymmetry, and make the investigation of neutrino oscillations a cutting-edge research area, at the juncture between particle physics and astrophysics.

We don't really know how to bring the mass of neutrinos into this picture: the SM doesn't say why the upper bounds found (of the order of a few eV/c^2) are so low. In all likelihood we will need a new type of physics, one functioning at energy levels much higher than the electroweak range (100 GeV).

Another major issue at stake is that the SM doesn't incorporate one of the fundamental forces: gravity. To sort this out scholars have proposed more exhaustive models containing the SM as low-energy limit. Some proposals view quarks and leptons as made of smaller subparticles (Compound Models), other models assume that the Higgs or the $W^\pm$ and Z^0 bosons are compounds, rather than seeking the unification of the electroweak and strong theories in terms of a unique symmetry group (GUTs, Grand

Unification Theories)² or postulating more encompassing symmetries such as Supersymmetry.³ Still other approaches attempt to include gravity in the picture (Supergravity).⁴ The energies we are talking about measure in TeV (=1000 GeV: Supersymmetry, Compound Models) or even higher, up to 10^{15} GeV (GUT) and 10^{19} GeV (Supergravity). Energies of 1 TeV are still accessible by the LHC, while the energies involved in GU Theories are out of reach for terrestrial accelerators. One would need “primal” particles, produced in the first instants of life of the universe, such as “magnetic monopoles” (isolated magnetic poles) or rare phenomena like the decay of the proton.

We have to point out the intimate relationship between the physics of the infinitely small (particles) and the

² These theories conjecture there is a relation between the strong force acting on quarks and the electroweak force of leptons and quarks. It would unify three fundamental interactions (electroweak and strong) and leave out only gravity. An argument supporting GU theories is the following. As the energy increases the inverses of the electroweak and strong coupling constants g , g' and ζ (ζ is related to the quark-gluon coupling constant α_s by $\alpha_s = \zeta^2/4\pi\hbar c$) converge to a common limit, becoming equal at around 10^{15} GeV. The original symmetry should be enlarged to a group that on one hand explained Grand Unification, and on the other generated, below 10^{15} GeV, the known symmetries of the SM. Thus we should have: $\text{SU}(5) \rightarrow (\text{below } 10^{15} \text{ GeV}) \rightarrow \text{SU}(3)_c \times \{\text{SU}(2)_w \times \text{U}(1)_{Y_w}\} \rightarrow (\text{below } 10^2 \text{ GeV}) \rightarrow \text{SU}(3)_c \times \text{U}(1)_{em}$. The group $\text{SU}(5)$ is the simplest possibility: it corresponds to the symmetry under rotations in a 5-dimensional space. The gist of the transformations described is that the single force, still unified at super-high energies, splits at 10^{15} GeV into the strong and electroweak forces, and then, below 10^2 GeV, splits again into electromagnetic, weak and strong.

³ Supersymmetry (SUSY) is a new framework designed with unification in mind. Whereas the transformations seen thus far always related particles of the same kind (bosons to bosons and fermions to fermions), supersymmetric theories allow for transformations of bosonic states into fermionic ones and conversely. It follows that bosons and fermions are different manifestations of unified states and coexist in the same multiplet. According to SUSY each known fundamental boson has a fermionic superpartner, characterized by the suffix “-ino” attached to the boson's name, whence *gluino*, *photino*, and so on. Similarly, each known fermion is associated to a bosonic partner labelled by the prefix “s-”: *selectron*, *squark*, et c. Moreover, the *spin* of superparticles differs by $\frac{1}{2}$ from that of the respective partners.

⁴ At microscopic lengths gravity becomes relevant when the energy reaches 10^{19} GeV, corresponding to 10^{-33} cm scales. Such energy levels existed in the early universe until 10^{-43} s after the Big Bang. An exhaustive theory must include the theory of gravity expressed in quantum language. Incorporating gravity has its own problems, related to both its quantisation and other issues that can't be overcome by renormalisation. The supersymmetric theory of gravity is called quantum supergravity, and seems very promising. Scientists have also formulated theories in which particles are objects that resemble infinitesimal pieces of string. These theories subsume quantum gravity in a rather easy way (*string theory*) and concern both bosonic states and supersymmetric partners (*superstring theories*). They need to be formulated in spaces of high dimension (at least 10), although it's far from obvious how to pass from the ordinary 4 dimensions of spacetime to these 10 or more: these extra dimensions should be somehow “hidden”.

physics of the infinitely large (the universe). For particle physicists the Big Bang is an accelerator having infinite energy. For example, at its alleged maximum energy of 14 TeV the LHC will allow us to study what happened 10^{-12} to 10^{-11} s after the Big Bang. Fundamental interactions, particles, astrophysics and cosmology have become deeply intertwined. Today we know that the universe is 13.7 billion years old, and during the cooling phase, 300,000 years after it was born, atoms began to form as photons lost the energy to annihilate them: it was then that electromagnetic radiation decoupled from matter. Around 200,000 years ago *Homo Sapiens* made its appearance on the earth and started relatively quickly to pose questions about the origin of the universe and his own existence.

We won't speculate about theories that in the (far or near) future might replace the SM, reducing it to a theory that works at the energies we can handle today. However, those who think that physics has already reached the frontiers of what there is to discover should be reminded of an anecdote. In 1878 a 20-year-old Max Planck chose thermodynamics as the topic for his final undergraduate dissertation, despite his adviser having discouraged him from undertaking a career in physics, since he thought that the discovery of the principles of thermodynamics 20 years or so earlier had put into place the last brick in the edifice of theoretical physics. What happened next became almost legendary.

14 Conclusions

Leon Lederman's book *The God Particle: If the Universe Is the Answer, What Is the Question?* [9] came out in 1993. Since then the "God particle" of the title, a.k.a. the Higgs boson, has been a blessing for columnists, editors and, I suppose, "advocates of the popularisation of science".⁵

The key offered by this fortunate expression is to hint at the research activity that aims at reconstructing the laws that some hypothetical Creator (whom we may picture holding a physics textbook whilst laughing heartily) presumably followed. The Higgs boson would then be the remaining "missing piece", another good expression. We have seen that scientific progress is shaped more by successive generalisations than filling in single gaps in a big

puzzle. And besides, this is certainly not the right place for venturing—nor does the author possess sufficient means to do so—along the difficult paths, often controversial and wonderful at times, of the relationship between science and religion.

We can, instead, muse on the analysis offered by Victor Weisskopf, an outstanding particle physicist of the last century:

It is often said that science has displaced man and his earth from the center of the universe, where man fondly believed himself to be, and has relegated him to some unimportant place. Our sun is only a small and undistinguished starlet in a corner of the enormous expanses of our galaxy, with many other stars like it. What is more, there are probably quite a number of other stars with planets where life has developed.

These might be depressing thoughts for some, but they may also have a different significance. The vastness of the universe, the billions of stars and the space between them are the necessary conditions for the development of matter from simple, unordered particles, to atoms and molecules, and finally to the large aggregates that form animals and sentient beings. The spots at which matter acquires more differentiated shape are very few and selected. They must be considered as the most developed and most outstanding parts of the universe, the parts where matter was able to make fuller use of its potentialities. We find ourselves, therefore, in a very privileged and central position, since our Earth is one of these spots.... Nature is reflected in the thoughts of these [thinking] beings.

It is not a simple reflection. In man's brain the impressions from outside are not merely registered: they produce concepts and ideas. They are the imprint of the external world on the human brain. Therefore, it is not surprising that, after a long period of searching and erring, some of the concepts and ideas in human thinking have come gradually closer to the fundamental laws of this world, that some of our thinking should reveal the true structure of atoms and the true movement of the stars. Nature, in the form of man, begins to recognize itself [11, pp. 275–276].

Translated from the Italian by Simon George Chiossi.

⁵ Originally Lederman had actually thought of *The Goddamn Particle* as a title, which the publisher didn't approve of. His reasons alluded to the elusive nature of the particle and the exorbitant costs of the research to detect it. Still, the final title was eventually vindicated. Lederman was convinced the Higgs boson existed to put intellects to the test: scientists might remain puzzled, as in the biblical account of the fate of Babel, or take up the challenge and realise "how beautiful the universe [that God created] is" (9, p. 22).

References

1. Bilenky, S.M., Galeotti, P., Piragino, G., Pontecorvo, G.: Le oscillazioni del neutrino. *Il Nuovo Saggiatore* **19**(3–4), 49–55 (2003). <http://prometeo.sif.it:8080/papers/online/sag/019/03-04/pdf/06.pdf>. Accessed 1 July 2014

2. Braibant, S., Giacomelli, G., Spurio, M.: *Particelle and interazioni fondamentali*, 2nd edn. Springer, Milan (2012)
3. Brown, L.M., Dresden, M., Hoddeson, L. (eds.): *Pions to Quarks: Particle Physics in the 1950s*. Cambridge University Press, Cambridge (1989)
4. CERN: observation of a new particle with a mass of 125 GeV. CSM Experiment, CERN; 2012. <http://csm.web.cern.ch/news/observation-new-particle-mass-125-gev>. Accessed 1 July 2014
5. Conversi, M.: Cinquanta anni di interazioni deboli: dalla teoria di Fermi alla scoperta dei bosoni pesanti. Università degli Studi di Pavia, *Quaderni del Dottorato*, 4 marzo (1986)
6. Fiorini, E.: Il neutrino, questo sconosciuto. *Il Nuovo Saggiatore* **23**(5–6), 47–57 (2007). <http://prometeo.sif.it:8080/papers/online/sag/023/05-06/pdf/05.pdf>. Accessed 1 July 2014
7. Hoddeson, L., Brown, L.M., Riordan, M., Dresden, M. (eds.): *The Rise of the Standard Model: Particle Physics in the 1960s and 1970s*. Cambridge University Press, Cambridge (1997)
8. Kane, G.: *Il giardino delle particelle*. TEA, Milan (2002)
9. Lederman, L.: *The God Particle: If the Universe Is the Answer, What Is the Question?*. Delta Publishing, New York (1993)
10. Masiero, A.: Il bosone di Higgs: la sua esistenza, la nostra esistenza. *Il Nuovo Saggiatore* **28**(3–4), 4–12 (2012). <http://prometeo.sif.it/papers/online/sag/028/03-04/pdf/03-scienza-in-primo-piano.pdf>. Accessed 1 July 2014
11. Weisskopf, V.: *Knowledge and Wonder: The Natural World as Man Knows It*, 2nd edn. MIT press, Cambridge, MA (1966)

Giulio Maltese was occupied for a number of years with the history of physics. His research concerned the history of rational mechanics, relativity and twentieth-century physics in Italy, with a particular focus on Fermi and the group of physicists in Via Panisperna. He passed away in 2013.