Ettore Majorana was born in Sicily in 1906. An extremely gifted physicist, he was a member of Enrico Fermi's famous group in Rome in the 1930s, before mysteriously disappearing in March 1938.

The great Sicilian writer, Leonardo Sciascia, was convinced that Majorana decided to disappear because he foresaw that nuclear forces would lead to nuclear explosives a million times more powerful than conventional bombs, like those that would destroy Hiroshima and Nagasaki. Sciascia came to visit me at Erice where we discussed this topic for several days. I tried to change his mind, but there was no hope. He was too absorbed by an idea that, for a writer, was simply too appealing. In retrospect, after years of reflection on our meetings, I believe that one of my assertions about Majorana's genius actually corroborated Sciascia's idea. At one point in our conversations I assured Sciascia that it would have been nearly impossible - given the state of physics in those days - for a physicist to foresee that a heavy nucleus could be broken to trigger the chain reaction of nuclear fission. Impossible for what Enrico Fermi called first-rank physicists, those who were making important inventions and discoveries, I suggested, but not for geniuses such as Majorana. Maybe this information convinced Sciascia that his idea about Majorana was not just probable, but actually true - a truth that his disappearance further corroborated.
There are also those who think Majorana's disappearance was related to spiritual faith and that he retreated to a monastery. This perspective on Majorana as a believer comes from his confessor, Monsignor Riccieri, who I met when he came from Catania to Trapani as Bishop. Remarking on his disappearance, Riccieri told me that Majorana had experienced "mystical crises" and that, in his opinion, suicide in the sea was to be excluded. Bound by the sanctity of confessional, he could tell me no more. After the establishment of the Erice Centre, which bears Majorana's name, I had the privilege of meeting Majorana's entire family. No one ever believed it was suicide. Majorana was an enthusiastic and devout Catholic and, moreover, he withdrew his savings from the bank a week before his disappearance. The hypothesis shared by his family and others who had the privilege of knowing him (Fermi's wife Laura was one of the few) is that he withdrew to a monastery.

Laura Fermi recalls that when Majorana disappeared, Enrico Fermi said to his wife, "Ettore was too intelligent. If he has decided to disappear, no-one will be able to find him. Nevertheless, we have to consider all possibilities." In fact, Fermi even tried to get Benito Mussolini himself to support the search. On that occasion (in Rome in 1938), Fermi said: "There are several categories of scientists in the world; those of second or third rank do their best but never get very far. Then there is the first rank, those who make important discoveries, fundamental to scientific progress. But then there are the geniuses, like Galilei and Newton. Majorana was one of these."

A genius, however, who looked on his own work as completely banal: once a problem was solved, Majorana did his best to leave no trace of his own brilliance. This can be witnessed in the stories of the neutron discovery and the hypothesis of the neutrinos that bear his name, as recalled below by Emilio Segré and Giancarlo Wick (on the neutron) and by Bruno Pontecorvo (on neutrinos). Majorana's comprehension of the physics of his time had a completeness that few others in the world could match.

**Oppenheimer's recollections**

Memories of Majorana had nearly faded when, in 1962, the International School of Physics was established in Geneva, with a branch in Erice. It was the first of the 150 schools that now form the Centre for Scientific Culture, which today bears Majorana's name. It is in this context that an important physicist of the 20th century, Robert Oppenheimer, told me of his knowledge of Majorana.

After having suffered heavy repercussions for his opposition to the development of weapons even stronger than those that destroyed Hiroshima and Nagasaki, Oppenheimer had decided to get back to physics while visiting the biggest laboratories at the frontiers of scientific knowledge. This is how he came to be at CERN, the largest European laboratory for subnuclear physics.
At this time, many illustrious physicists participated in a ceremony that dedicated the Erice School to Majorana. I myself - at the time very young - was entrusted with the task of speaking about the Majorana neutrinos. Oppenheimer wanted to voice his appreciation for how the Erice School and the Centre for Scientific Culture had been named. He knew of Majorana’s exceptional contributions to physics from the papers he had read, as any physicist could do at any time. What would have remained unknown was the episode he told me as a testimony to Fermi’s exceptional opinion of Majorana. Oppenheimer recounted the following episode from the time of the Manhattan Project, which in the course of only four years transformed the scientific discovery of nuclear fission into a weapon of war.

There were three critical turning points during the project, and during the executive meeting to address the first of these crises, Fermi turned to Eugene Wigner and said: "If only Ettore were here." The project seemed to have reached a dead-end in the second crisis, during which Fermi exclaimed once more: "This calls for Ettore!" Other than the project director himself (Oppenheimer), three people were in attendance at these meetings: two scientists (Fermi and Wigner) and a military general. After the "top secret" meeting, the general asked Wigner, who this "Ettore" was, and he replied: "Majorana". The general asked where Majorana was so that he could try to bring him to America. Wigner replied: "Unfortunately, he disappeared many years ago."

By the end of the 1920s, physics had identified three fundamental particles: the photon (the quantum of light), the electron (needed to make atoms) and the proton (an essential component of the atomic nucleus). These three particles alone, however, left the atomic nucleus shrouded in mystery: no-one could understand how multiple protons could stick together in a single atomic nucleus. Every proton has an electric charge, and like charges repel each other. A fourth particle was needed, heavy like the proton but without electric charge. This was the neutron, but no-one knew it at the time.

Then Frédéric Joliot and Irène Curie discovered a neutral particle that can enter matter and expel a proton. Their conclusion was that it must be a photon, because at the time it was the only known particle with no charge. Majorana had a different explanation, as Emilio Segré and Giancarlo Wick recounted on different occasions, including during visits to Erice. (Both Segré and Wick were enthusiasts for what the school and the centre had become in only a few years, all under the name of the young physicist that Fermi considered a genius alongside Galilei and Newton). Majorana had explained to Fermi why the particle discovered by Joliot and Curie had to be as heavy as a proton, even while being electrically neutral. To move a proton requires something as heavy as the proton, thus a fourth particle must exist, a proton with no charge. And so was born the correct interpretation of what Joliot and Curie discovered in France: the existence of a particle that is as heavy as a proton but without electrical charge. This particle is the indispensable neutron. Without neutrons, atomic nuclei could not exist.

Fermi told Majorana to publish his interpretation of the French discovery right away. Majorana, true to his belief that everything that can be understood is banal, did not bother to do so. The discovery of the neutron is in fact justly attributed to James Chadwick for his experiments with beryllium in 1932.

**Majorana’s neutrinos**

Today, Majorana is particularly well known for his ideas about neutrinos. Bruno Pontecorvo, the "father" of neutrino oscillations, recalls the origin of Majorana neutrinos in the following way: Dirac discovers his
famous equation describing the evolution of the electron; Majorana goes to Fermi to point out a fundamental detail: "I have found a representation where all Dirac matrices are real. In this representation it is possible to have a real spinor that describes a particle identical to its antiparticle."

The Dirac equation needs four components to describe the evolution in space and time of the simplest of particles, the electron; it is like saying that it takes four wheels (like a car) to move through space and time. Majorana jotted down a new equation: for a chargeless particle like the neutrino, which is similar to the electron except for its lack of charge, only two components are needed to describe its movement in space-time - as if it uses two wheels (like a motorcycle). "Brilliant," said Fermi, "Write it up and publish it."

Remembering what happened with the neutron discovery, Fermi wrote the article himself and submitted the work under Majorana's name to the prestigious scientific journal *Il Nuovo Cimento* (Majorana 1937). Without Fermi’s initiative, we would know nothing about the Majorana spinors and Majorana neutrinos.

The great theorist John Bell conducted a rigorous comparison of Dirac's and Majorana's "neutrinos" in the first year of the Erice Subnuclear Physics School. The detailed version can be found in the chapter that opens the 12 volumes published to celebrate Majorana’s centenary. These volumes describe the highlights leading up to the greatest synthesis of scientific thought of all time, which we physicists call the Standard Model. This model has already pushed the frontiers of physics well beyond what the Standard Model itself first promised, so now the goal is the Standard Model and beyond.

Today we know that three types of neutrinos exist. The first controls the combustion of the Sun's nuclear engine and keeps it from overheating. One of the dreams of today’s physicists is to prove the existence of Majorana's hypothetical neutral particles, which are needed in grand unification theory. This is something that no-one could have imagined in the 1930s. And no-one could have imagined the three conceptual bases needed for the Standard Model and beyond.

**Particles with arbitrary spin**

In 1932 the study of particles with arbitrary spin was considered at the level of a pure mathematical curiosity, and Majorana’s paper on the subject remained quasi-unknown despite being full of remarkable new ideas (Majorana 1932). Today, three-quarters of a century later, this mathematical curiosity of 1932 still represents a powerful source of new ideas. In fact in this paper there are the first hints for supersymmetry, spin-mass correlation and spontaneous symmetry breaking (SSB) - three fundamental concepts underpinning the Standard Model and beyond. This means that our current conceptual understanding of the fundamental laws of nature was already in Majorana’s attempts to describe particles with arbitrary spins in a relativistically invariant way.

Majorana starts with the simplest representation of the Lorentz group, which is infinite-dimensional. In this representation the states with integer (bosons) and semi-integer (fermions) spins are treated equally. In other words, the relativistic description of particle states allows bosons and fermions to exist on equal footing. These two fundamental sets of states are the first hint of supersymmetry.

Another remarkable novelty is the correlation between spin and mass. The eigenvalues of the masses are given by a relation of the type \( m = m_0/(J+1/2) \), where \( m_0 \) is a given constant and \( J \) is the spin. The mass decreases with the increasing value of the spin, the opposite of what would come, many decades later, in
the study of the strong interactions between baryons and mesons (now known as Regge trajectories). As a consequence of the description of particle states with arbitrary spins, this remarkable paper also contains the existence of imaginary mass eigenvalues. We know today that the only way to introduce real masses without destroying the theoretical description of nature is through the mechanism of SSB, but this could not exist without imaginary masses.

In addition to these three important ideas, the paper also contributed to a further development: the formidable relation between spin and statistics, which would have led to the discovery of another invariance law valid for all quantized relativistic field theories, the celebrated PCT theorem.

Majorana’s paper shows first of all that the relativistic description of a particle state allows the existence of integer and semi-integer spin values. However, it was already known that the electron must obey the Pauli exclusion principle and that it has semi-integer spin. Thus the problem arose of understanding whether the Pauli principle is valid for all semi-integer spins. If this were the case it would be necessary to find out the properties that characterize the two classes of particles, now known as fermions (semi-integer spin) and bosons (integer spin). The first of these properties are of statistical nature, governing groups of identical fermions and groups of bosons. We now know that a fundamental distinction exists and that the anticommutation relations for fermions and the commutation relations for bosons are the basis for the statistical laws governing fermions and bosons.

The spin-statistics theorem has an interesting and long history, the main players of which are some of the most distinguished theorists of the 20th century. The first contribution to the study of the correlation between spin and statistics comes from Markus Fierz with a paper where the case of general spin for free fields is investigated (Fierz 1939). A year later Wolfgang Pauli comes in with his paper also "On the Connection Between Spin and Statistics" (Pauli 1940). The first proofs, obtained using only the general properties of relativistic quantum field theory and which include microscopic causality (also known as local commutativity), are due to Gerhart Lüders and Bruno Zumino, and to N Burgyne (Lüders and Zumino 1958; Burgoyne 1958). Another important contribution, which clarifies the connection between spin and statistics, came three years later with the work of G F Dell'Antonio (Dell'Antonio 1961).

It cannot be accidental that the first suggestion of the existence of the PCT invariance law came from the same people engaged in the study of the spin-statistics theorem, Lüders and Zumino. These two outstanding theoretical physicists suggested that if a relativistic quantum field theory obeys the space-inversion invariance law, called parity (P), it must also be invariant for the product of charge conjugation (particle-antiparticle) and time inversion, CT. It is in this form that it was proved by Lüders in 1954 (Lüders 1954). A year later Pauli proved that PCT invariance is a universal law, valid for all relativistic quantum field theories (Pauli 1955).

This paper closes a cycle started by Pauli in 1940 with his work on spin and statistics where he proved already what is now considered the classical PCT invariance, as it was derived using free non-interacting fields. The validity of PCT invariance for quantum field theories was obtained in 1951 by Julian Schwinger, a great admirer of Majorana (Schwinger 1951). It is interesting to read what Arthur Wightman, another of Majorana’s enthusiastic supporters, wrote about this paper by Schwinger: "Readers of this paper did not generally recognize that it stated or proved the PCT theorem" (Wightman 1964). It is similar for those who,
reading Majorana's paper on arbitrary spins, have not found the imprinting of the original ideas discussed in this short review of the genius of Majorana.

**Further reading**


E Majorana 1937 *Nuovo Cimento* 14 171.


**About the author**

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