Part I

Introducing the character

1

Life and myth

On Saturday March 26, 1938 the director of the Institute of Physics at the University of Naples in Italy, Antonio Carrelli, received a mysterious telegram. It had been sent the previous day from the Sicilian capital Palermo, some 300 km across the Tyrrhenian Sea, and read: "Don't worry. A letter will follow. Majorana." That same Saturday, Ettore Majorana – who had just been appointed as full professor of theoretical physics at the university at the age of 31 – had not turned up to give his three-weekly lecture on theoretical physics. By Sunday the promised letter had reached Carrelli. In it Majorana wrote that he had abandoned his suicidal intentions and would return to Naples, but it revealed no hint of where the illustrious physicist might be. The picture was quickly becoming clear: Majorana had disappeared.

Worried by these circumstances, Carrelli called his friend Enrico Fermi in Rome, who immediately realized the seriousness of the situation. Fermi was working in his laboratory with the young physicist Giuseppe Cocconi at the time. In order to give him an idea of the seriousness of the loss to the community of physicists caused by Majorana's disappearance, Fermi told Cocconi:

> You see, in the world there are various categories of scientists: there are people of a secondary or tertiary standing, who do their best but do not go very far. There are also those of high standing, who come to discoveries of great importance, fundamental for the development of science [...]. But then there are geniuses like Galileo and Newton. Well, Ettore was one of them. Majorana had what no-one else in the world had.[1]

1.1 Fortunes and misfortunes of a genius

Physicists working in several areas of research know quite well the name of Ettore Majorana, since it is currently associated with fundamental concepts like *Majorana neutrinos* in particle physics and cosmology or *Majorana fermions* in condensed

[1] Cocconi letter to Edoardo Amaldi, dated July 18, 1965. Reported in Ref. [1].

matter physics. For non-specialists, the name of Ettore Majorana is usually intimately related to the fact that he disappeared rather mysteriously in 1938 and was never seen again. However, Ettore Majorana's fame rests mainly – until now – on testimonies by the scholars who had the chance to know him personally [1, 2], like, for example, Bruno Pontecorvo, a younger colleague of Majorana at the Institute of Physics in Rome directed by Fermi:

> Some time after joining the Fermi group, Majorana already had such an erudition and reached such a high level of comprehension of physics that he was able to discuss with Fermi about scientific problems. Fermi himself held him to be the greatest theoretical physicist of our time. He often was astounded [...]. I remember exactly these words that Fermi spoke: "Once a problem has already been posed, no one in the world is able of solving it better than Majorana." [3, 4]

Indeed, Majorana earned great respect in Fermi's Institute, where he was considered a prodigy by all its associates, including Emilio Segrè, Edoardo Amaldi, Gian Carlo Wick, and many other scientists visiting Rome from their native countries in Europe and America. Werner Heisenberg, for example, who knew him when he visited Leipzig in 1933 (see below), considered Majorana a "very good physicist. [...] He was a very brilliant man. [...] He did excellent work. [...] I tried always to induce him to write papers and so he did finally write a very good paper" [5]. And it is quite intriguing and surprising that, while lecturing on nuclear forces at the VII Solvay Congress in 1933, Heisenberg mentioned only very rarely, and in a very hidden way, his own contribution to the problem, while *almost always* used expressions such as "d'apres Majorana," "en suivant l'exemple de Majorana," "comme y a insisté Majorana," "nous choisirons avec Majorana." [6]

A more complete acknowledgment of Majorana's work, during his lifetime, comes again from Fermi; by borrowing his own words, given in 1937 in the occasion of a meeting of the board in charge of the competition for a new full professorship in theoretical physics in Italy:

> Without listing his works, all of which are highly notable both for their originality of the methods as well as for the importance of the results achieved, we limit ourselves to the following.
>
> In modern nuclear theories, the contribution made by this researcher to the introduction of the forces called "Majorana forces" is universally recognized as the one, among the most fundamental, that allows us to understand theoretically nuclear stability. The work of Majorana today serves as a basis for the most important research in this field.
>
> In atomic physics, the merit of having resolved some of the most intricate questions on the structure of spectra through simple and elegant considerations of symmetry is due to Majorana.
>
> Lastly, he devised a brilliant method that deals with positive and negative electrons in a symmetric way, eventually eliminating the necessity to rely on the extremely artificial and

unsatisfactory hypothesis of an infinitely large electric charge diffused in space, a question that had been tackled by many other scholars without success. [7, 8]

With this justification, the board, chaired by Fermi, proposed to apply (for only the second time) a special bill passed a few years earlier in order to give a chair to the Nobel laureate Guglielmo Marconi, and suggested to the Minister of National Education "to appoint Majorana as full professor of Theoretical Physics at some University of the Italian kingdom, for high and well-deserved repute, independently of the competition rule." The Minister accepted the proposal: evidently, such a reputation was sufficiently established on the basis of just a few (nine) papers published by the Italian scientist.

Unfortunately enough, however, the University of Naples hosted his talent for three months only, until the end of March 1938, when Majorana gave his last lesson.

He was always extremely pessimistic about physics. [...] I would say that he was perhaps not pessimistic about physics especially but rather about life in general. He was that kind of difficult fellow. Well, sometimes I thought perhaps he had had very difficult experiences in his life with other people, perhaps his girls or so. I don't know. Anyway, I couldn't make out why he, being such a young man, and such a brilliant young man, could always be so pessimistic. He was a very attractive fellow, so I liked him in our Leipzig group. I tried to see him frequently, and we had him at our ping pong games. Then I would sit down with him and ask him about not only physics but his private things and so on. So I tried to keep in touch with him. He was a very attractive fellow but very nervous so that he would get in a state of some excitement if you talked to him. So he was a bit difficult. Then all of a sudden he disappeared. I was very sorry to hear of it. [5]

It is quite striking that Majorana left an indelible mark of his science on a number of people, like Heisenberg, *almost entirely independent* of his own will, due to his extremely shy nature.

It was very difficult [to communicate with Majorana]. Of course, people tried to talk to him and he was always very kind and very polite and very shy. It's very difficult to get something out from him. But still, one could see at once that he was a very good physicist. When he made a remark it was to the point. [9]

Indeed, *any* people who knew Majorana share the same opinion (starting, of course, with his friends and colleagues in Rome), and it is a matter of fact that several nice anecdotes developed about his genius. This only apparently contrasts with a rather poor list of papers (only nine) authored by Majorana, since his peculiar character prevented him from publishing the results he obtained during his own researches, as alluded to by Heisenberg in the preceding quotation and, especially, testified by his colleagues at the Institute of Physics in Rome. The direct result of such a business was that his published contributions to physics were not at all widespread for decades (with the notable exception of his work on nuclear forces,

sponsored by Heisenberg), while his unpublished contributions did not affect the development of physics. The fact remains, however, that a number of results he did obtain – and not publish – were re-discovered only later, and much later, by other scholars, while some others still wait for proper consideration. The relevance of such a gap can only be glimpsed – for the moment – from testimonies who personally met Majorana. It is, therefore, useful to recall a final quotation from Fermi, who was very well known to be not at all prone to rave about anyone:

> Able to develop audacious hypotheses and, at the same time, to criticize acutely his own work and that of others; highly skilled in calculations and a deep-routed mathematician who never loses the very essence of the physical problem behind the veil of numbers and algorithms, Ettore Majorana has at the highest level that rare combination of abilities which form a first-rank theoretical physicist. Indeed, in the few years during which his activity has been carried out, until now, he has been able to outclass the attention of scholars from all over the world, who recognized, in his works, the stamp of one of the greatest minds of our times and the promise of further conquests.[2]

These further conquests will be the subject of the following chapters.

1.2 Family and university training

Ettore Majorana was born on August 5, 1906 in Catania, a town in Sicily, Italy, to Fabio and Salvatrice (Dorina) Corso. Engineer Fabio Majorana, the chief of the local telephone company, was the last of five sons of Salvatore Majorana Calatabiano, who was Minister of Agriculture, Industry, and Trade in the two cabinets chaired by Prime Minister Agostino Depretis at the end of the nineteenth century. Ettore's uncles also played key roles in the Italian society of their time. Giuseppe, a professor of finance and economy, was Rector of the University of Catania and deputy in three legislatures of the Italian Parliament. Angelo, a professor of constitutional law and of sociology, was Rector of the same university and acted as under-secretary and as minister (twice) in the cabinet chaired by Giovanni Giolitti. Quirino Majorana was, instead, a talented and illustrious experimental physicist, professor at the University of Bologna after Augusto Righi; he directed the Italian Physical Society for many years. Finally Dante, a lawyer, was a deputy and Rector too. The two younger sisters of Fabio Majorana, Elvira and Emilia, married important political personalities. The relevance and importance of the Majorana family in Italian life is thus clear. Also, Ettore's mother belonged to a rich family of farmers and, from her marriage to Fabio Majorana, three sons and two daughters were born: Rosina, Salvatore (a lawyer and a lover of philosophy), Luciano (a civil engineer who specialized in the making

[2] Fermi letter to Prime Minister Benito Mussolini, dated July 27, 1938. Reported in Ref. [1]. See also Ref. [10].

of aeronautical constructions and instruments for optical astronomy), Ettore, and Maria.

The pronounced attitudes of the child Ettore, as well as his interest in physical sciences and astronomy, were cultivated directly by his father Fabio, with whom a particularly affectionate feeling was established. Studies corresponding to the first school years were performed at home (under the direction of Ettore's father), but when Ettore was eight years old his mother decided that the young genius should study at a prestigious boarding-school in Rome, namely at the *Istituto parificato Massimiliano Massimo*, managed by Jesuits. His mother Dorina moved with her sons and daughters to Rome in 1921, followed by Ettore's father three years later, when the telephone company became a state company and he was transferred to Rome. Following a common procedure, while approaching his final high-school examinations, for the last years of his course of studies Ettore (and his brother Luciano) moved from the *Istituto Massimo* to the equally prestigious *Liceo Statale Torquato Tasso*, where Ettore received his degree of *licenza liceale* in the summer of 1923.

Majorana joined the Faculty of Engineering at the University of Rome in November 1923, and remained there (where he excelled) until the start of the fifth year of his course. Among his teachers, we may recall the renowned mathematicians Guido Castelnuovo, Tullio Levi-Civita, Francesco Severi, and Francesco Tricomi, as well as the physicist Orso Mario Corbino, Director of the Institute of Physics; their high-level courses gave him a solid preparation in calculus, geometry, rational mechanics, and experimental physics. An amusing anecdote regarding Majorana, and narrated by a colleague of his at the Faculty of Engineering, Emilio Segrè, is the following:

> Once, not having sufficiently prepared a lecture, Severi started a proof of a theorem the wrong way. Majorana immediately whispered that he would soon be in trouble, so we all anticipated what was to come. After a minute or two, Severi's face reddened, and it became obvious that he did not know how to proceed. Some voices then murmured: "Majorana predicted it." Severi did not know who Majorana was, but said haughtily, "Then let Mr. Majorana come forward." Ettore was pushed to the blackboard, where he erased what Severi had written and gave the correct proof. [11]

In addition to Emilio Segrè, Majorana could rely on several other friends also attending engineering. First, there were his brother Luciano and Gastone Piqué, a very dear friend of his since high school, while other classmates included Enrico Volterra (son of the well-known mathematician Vito Volterra), Giovanni Enriques (son of Federigo Enriques, another illustrious mathematician and epistemologist), and Giovanni Ferro-Luzzi.

In his third year at university, Majorana – like his close friends – transferred to the School of Engineering (for the final three years of his course), finding the

courses much less interesting than in the previous preparatory biennium. Indeed, according to Edoardo Amaldi, another fellow student (still in the biennium):

> While he was at the School of Engineering, Majorana, together with some of his fellow students, grew very critical of the way in which some of the subjects were taught: he felt that too much time was spent on unnecessary detail and not enough on the general synthesis needed for serious and systematic scientific study. This deep-rooted conviction of his frequently gave rise to lively, and sometimes heated, discussions with some of the professors. [10]

Such a situation endured for almost two years, but then something unexpected happened.

In June 1927, the Director of the Institute of Physics at the University of Rome, Orso Mario Corbino, launched a curious "appeal" to his students at the Faculty of Engineering. According to him, "in the present state of rapid change now prevailing in physics all over Europe, and with Fermi's appointment at Rome, an exceptional period has opened up for young people who have already shown sufficient ability and are willing to make an exceptional effort in theoretical and experimental study" [11]. In practice, the intent was to entice some of the most brilliant young minds into studying physics, and then recruit appropriate members for the newborn group created by Fermi.

Amaldi and, a few months later, Segrè rose to the challenge, and moved from engineering to physics, thus enlarging the group comprising only Fermi and the experimentalist Franco Rasetti, who had been hired earlier by Corbino as his assistant, in accordance with his plan of supporting a rapid development of physics in Italy [11]. In their new circle, Amaldi and Segrè obviously told Fermi and Rasetti of Majorana's exceptional gifts:

> You could ask Majorana things that you couldn't ask anybody else in the world. He was a prodigy. [...] You could get him to integrate, I don't know, a very complicated integral and so on; he would look at it and tell you the answer without even writing it. He could do feats of this type. [12]

Urged repeatedly by his friends Amaldi and Segrè, in the fall of the same year, 1927, Majorana eventually agreed to meet Fermi. The two beautiful minds immediately started talking about the statistical model of atoms that Fermi was working on, later to be known as the Thomas–Fermi model. As is well known, such a model involves a complicated non-linear differential equation, whose analytic solution was unknown, but Fermi had managed to obtain a numerical table of approximate values for it. In that room of the Institute of Physics in Rome, Majorana carefully followed Fermi's reasoning, asked a few questions, and left the Institute.

> The next day, towards the end of the morning, he again came into Fermi's office and asked him without more ado to show him the table which he had seen for a few moments the day

before. Holding this table in his hand, he took from his pocket a piece of paper on which he had worked out a similar table at home in the last twenty-four hours. [...] He compared the two tables and, having noted that they agreed, said that Fermi's table was correct: he then went out of the office and left the Institute. [10]

What seems nothing more than an amusing anecdote, as recalled by Rasetti, Segrè and Amaldi, has since been carefully tested on scientific grounds, as we will see in Chapter 4. As if satisfied that Fermi had passed his "examination," Majorana decided to leave Engineering and join Fermi's group:

A few days later he switched over to Physics and began to attend the Institute regularly. [10]

1.3 Lone physicist in the Fermi group

The final two years of Majorana's university career then developed at the Institute of Physics and, among the last few (and new) courses that he attended we mention that of Higher Experimental Physics held by Antonino Lo Surdo (the discoverer, independently of Johannes Stark, of the homonymous physical effect induced by an electric field on light spectra), and that of Mathematical Physics delivered by Vito Volterra. However, in addition to the "institutional" courses, Majorana also participated in "private" lectures held by Fermi in his office, and addressed to his students and collaborators.

Fermi taught us privately. [...] He gave a course in which he explained exactly what is contained in [his book] *Introduzione alla fisica atomica*, which one can get out of the library and see exactly what he taught. [...] Then, I would say three times a week, in the afternoon at five o'clock or something like this, he would give us a private lecture. To Amaldi, to me, to Rasetti, and Majorana, and occasionally Corbino would come. [...] Majorana very often would say, "Well, it's beneath my dignity. Why should I learn these things? You are doing it in a childish way; it should be done this way." [...] Fermi didn't react to that. Except a year or two later he decided that we were not worthy to be present at the interviews [when] Majorana [was there], and then they would closet themselves together because they went very fast in very difficult theory and so on. [12]

Majorana's personal contribution to the Fermi group was, then, substantial from the beginning, but it developed in different ways through the years.

In July 1928, when still a student and well before his graduation in physics, Majorana completed his first published paper, "On the splitting of the Roentgen and optical terms caused by the electron rotation and on the intensity of the cesium lines," in collaboration with his later close friend Giovanni Gentile Jr., where they derived the ionization energy of an electron in the $3d$ orbit of gadolinium and uranium, and, in addition, calculated the fine structure splitting of different (X-ray transition) spectroscopic terms in gadolinium, uranium, and caesium by applying first-order perturbation theory to the recently developed Dirac

equation. Gentile, the son of the renowned Italian philosopher Giovanni Gentile, graduated in physics at the University of Pisa in November 1927, but soon after he moved to the Institute of Physics in Rome, where he spent about six months before departing for a one-year stay in Berlin (working with Erwin Schrödinger) and, then, another one-year stay in Leipzig (working with Heisenberg). Fermi discussed the results obtained by Gentile and Majorana on spin-orbit couplings and intensity ratios at a restricted conference held in Leipzig that same year (1928) under the chairmanship of Peter Debye, where he was invited to report the results of the work performed in Rome [13].

This was, however, not at all the only contribution given by Majorana to the study of some applications of the Thomas–Fermi atomic model carried out in those years by the Fermi group. Apart from the semi-analytic solution of the Thomas–Fermi equation already mentioned, as we will see in Chapter 4, Majorana studied the problem of an atom in a weak external electric field, i.e. atomic polarizability, and obtained an expression for the electric dipole moment for a (neutral or arbitrarily ionized) atom. Furthermore, he also started to consider the application of the statistical method to molecules, rather than single atoms, studying the case of a diatomic molecule with identical nuclei. Finally, Majorana also considered the second approximation for the potential inside the atom, beyond the Thomas–Fermi approximation, with a generalization of the statistical model of neutral atoms to those ionized n times. Unfortunately, Majorana did not publish anything on these studies. The attitude of Majorana not to spread the results of a given research, until its perfect refinement (according to *his* hypercritical judgement) was completed or when they were considered premature, manifested here for the first time. However, Fermi succeeded in convincing him to present (some of) his results to the 1928 annual meeting of the Italian Physical Society, held at the Institute of Physics in Rome in December. Majorana effectively delivered a talk at the meeting, but refused to publish his own work in the form of a regular article: "the researches performed till now are still too much scarce to fully appreciate such results" [14]. We will see that this is typical of how the personality of Majorana developed.

The first work on nuclear physics performed within the Fermi group is also associated with the name of Majorana: indeed, in July 1929 he graduated in physics by defending his master thesis on "the quantum theory of radioactive nuclei." The Fermi group did not become effectively involved in nuclear physics until 1933, but it is not particularly strange that such a subject entered in a thesis: although not applicable to Majorana, Fermi did not like to assign subjects for a thesis since he did not easily find subjects simple enough for beginners (he usually thought of problems that interested him personally but were too difficult for students) [15]. Nuclear physics was among the subjects studied by Majorana for several years,

independently of the main research topics of the Fermi group, until his famous theory of nuclear exchange forces published in 1933 (see Section 1.4).

After graduation, he continued to attend the Institute of Physics in Rome:

> He spent his time in the library, where he mainly studied the works of Dirac, Heisenberg, Pauli, Weyl and Wigner. The last two authors were perhaps the only ones for whom he expressed unqualified admiration. This was due, at least to a large extent, to his particularly lively, almost prophetic, interest in group theory and its application to physics. [10]

Indeed, particularly relevant for Majorana was his "discovery" of the book by Hermann Weyl on *Gruppentheorie und Quantenmechanik* [16], which profoundly influenced his entire scientific thought and work. The synthetic, clear, and general approach offered by group theory was well appreciated by Majorana and only a very few other scientists in the world, until its re-discovery in 1950s and 1960s.

Although not *canonically* involved in the researches performed by the Fermi group, true to his style[3] Majorana did get involved in the studies of his friends and colleagues (including Fermi). Some illuminating examples, among many others, are the following.

In 1931–2 Segrè was in Hamburg, thanks to a fellowship that allowed him to work with Otto Robert Frisch in the group headed by Otto Stern, experimenting on atoms in a variable magnetic field (in practice, they were setting up an experiment to generalize the famous work by Stern and Gerlach on spatial quantization). However, the interpretation of their results required the solution of complicated theoretical problems, which they were not able to solve, so Segrè asked for help from his friend Majorana [12], who then produced the appropriate theory. In this case, Majorana did publish the theory in his paper N.6, which then became a seminal work for the treatment of non-adiabatic spin-flips, now included in quantum mechanics textbooks and recently re-discovered in atomic and molecular collision physics at low energy, as well as in nuclear and particle physics.

At almost the same time, George Placzeck joined the Fermi group in Rome for one year, working with Amaldi on the rotational spectrum of ammonia molecules observed in the Raman effect [10]. Majorana was regularly informed of such studies, which evidently interested him so much that he autonomously solved the problem of the determination of ammonia oscillation frequencies, relating them to the tetrahedral structure of the molecule. This work was, however, not published, and we know about it only through his own research notes [17] [18].

Fermi benefitted from help given by Majorana on several occasions, as, for example, when he and Segrè were working on the hyperfine structures of atomic spectra. In the paper published by Fermi and Segrè in 1933, the authors explicitly

[3] No papers published by Majorana have a co-author, with the exception of the already mentioned first paper, in collaboration with Gentile.