# Why did Ettore Majorana invent the "Majorana Neutrino" and is the Neutrino really "Majorana"?

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*Abstract*: In 1930, the situation for the single beta decay was extremely difficult. The decay of an element with charge $Z$ to charge $Z+1$ with the emission of an electron requires, by means of energy conservation, a fixed energy of the electron emitted, and not the measured continuum extending from zero to a maximum value. To solve this problem, Wolfgang Pauli sent his famous letter from Zürich to a meeting in Tübingen, in which he proposed that in the beta decay a second extremely light particle, the "neutron", is created. Later, after the "neutron" was detected, Enrico Fermi called this particle "neutrino".
In 1937, three chairs in the field of the new Quantum Mechanics were established in Italy. Fermi was the chairman of the selection committee. As a surprise – after the short-list was finished – Ettore Majorana, who lived very secluded in an apartment of the family in Rome, applied for one of the chairs. Fermi declared that he was the best candidate and must be given a chair. Fermi succeeded to obtain a fourth chair for Naples. To compete for the chair, Majorana had to submit a paper. This was the famous "Majorana neutrino" publication. He showed that the solution of the Dirac equation allows a neutral fermion, which is particle and its own antiparticle, the "Majorana neutrino". If a neutral fermion is different from its antiparticle, we call it a "Dirac particle". In November 1937, he was appointed to the chair in Naples.

*Keywords*: Ettore Majorana, Majorana neutrino, Dirac particle, beta decay.

## 1. Introduction

In 1930 the situation with the single beta decay was extremely difficult. The single beta decay emits an electron for a transition between a fixed initial and a fixed final nuclear state. The electron should therefore have a fixed energy. But it shows a continuum spectrum with the upper end there, where we expect the fixed electron energy. Niels Bohr was even prepared to give up energy conservation for atomic processes. Wolfgang Pauli proposed, in a letter from the ETH Zürich to a meeting on radioactivity in Tübingen, that the problem is solved by an additional particle, which he called "neutron", and which was renamed after the detection of the "true" neutron in 1932 to "neutrino" by Enrico Fermi. Pauli remarked, in his letter, that this particle can never be detected, since it has an extreme small mass and interaction. Pauli was right concerning

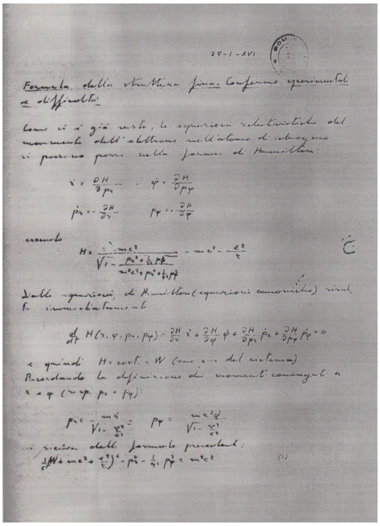
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**Fig. 1.** First page of the lecture notes by Ettore Majorana on the Dirac equation in Naples, starting on January 25th, 1938. One should remark the date: 25 January XVI. Mussolini did not count "after Christ" but "after the March to Rome" of his followers in October 1922, the date when he took power in Italy. The copy of the lecture notes was given to me by Prof. Aldo Covello from Naples.

the existence of an additional particle, the "neutrino", but he was wrong in the assumption, that this particle can never be found. The experimentalists even detected three different neutrinos and three anti-neutrinos: electron neutrinos (Cowen, Reines *et al.* 1956), muon neutrinos (Danky *et al.* 1962) and tauon neutrinos (Kodama *et al.* 2001).

## 2. Why did Ettore Majorana invent the "Majorana neutrino"?

After Ettore Majorana returned from Heisenberg in Leipzig during August 1933, he lived till 1937 practically alone in an apartment of the Majorana family in Rome, with curtains closed. Only his physics friends sent him sometimes a hair cutter. During this time, he published no paper.

In 1937 three Theoretical Physics chairs were installed in the new field of Quantum Mechanics. Enrico Fermi (1901-1954) was the chairman of the selection committee. The short-list for the competition was:

1. Gian Carlo Wick (1909-1992);
2. Giulio Racah (1909-1965);
3. Giovanni Gentile Jr (1906-1942).[1]

[1] His father, Giovanni Gentile Senior, was Minister of Education of Mussolini from Castelvetrano, Sicily.

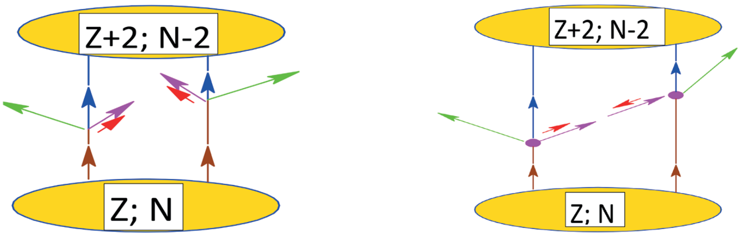


**Fig. 2.** Left: two-neutrino double beta decay represents two simultaneous single beta decays and cannot distinguish between Majorana and Dirac neutrinos. This decay is allowed for Dirac and Majorana neutrinos. Right: neutrinoless double beta decay is only possible for massive Majorana neutrinos. For a finite mass, helicity is not a good quantum number and at the left vertex an antineutrino is emitted while it is absorbed at the right vertex as neutrino (only possible for Majorana neutrinos). In order not to be helicity forbidden by the spin direction, the exchanged neutrino must have a mass. So, the detection of the neutrinoless double beta decay would show the Majorana character of the neutrino.

After the short list was completed, Ettore Majorana applied surprisingly for one of the chairs. Enrico Fermi was convinced that Ettore was the best candidate of all three. Due to the redoubtably good scientific reputation of Ettore Majorana, the committee used the law of "Chiara Fama" and did not ask for references. Fermi succeeded probably with the help of Giovanni Gentile Senior to establish a fourth chair located at Naples. To compete for this chair, Ettore Majorana had to submit a publication: this is the famous "Majorana neutrino" paper (Majorana 1937), *Teoria simmetrica dell'elettrone e del positrone*. In October 1937, Ettore accepted the position in Naples and on January 25, 1938 he started with his lecture on the Dirac equation.

I want here not detail the disappearance of Ettore Majorana on 26 of March 1938. The most authentic description of the disappearance is given by Erasmo Recami (1987) in his book *Il caso Majorana* and a book by Leonardo Sciascia (1975), *La Scomparsa di Majorana* (a bestseller, more than 600000 copies sold), aiming more to entertainment than to accuracy. The aim of this contribution is to investigate the question, if and how one can distinguish experimentally between Dirac and Majorana neutrinos. We shall see that the *experimentum crucis* is the neutrinoless double beta decay. In addition, we shall discuss the Majorana fermions in Solid State Physics connected with superconductivity, which might be a step to the Quantum Computer by more stable quantum-bits (q-bits).

## 3. Dirac or Majorana neutrinos?

The single beta decay and the two-neutrino double beta decay cannot differentiate between Majorana and Dirac neutrinos. This can the neutrinoless double beta decay, which is forbidden for Dirac and allowed for Majorana neutrinos. So, if the neutrinoless double beta decay is detected, the neutrino must be "Majorana", and worldwide several collaborations search for the neutrinoless double beta decay. Two of the most promising experiments are performed in the Gran Sasso underground laboratory of the INFN (Istituto Nazionale di Fisica Nucleare): GERDA (Agostini *et al.* 2018) for the decay $^{76}Ge \rightarrow {}^{76}Se$ is performed mainly by groups in Heidelberg, München and Tübingen. With the Q-value $Q_{\beta\beta}$ = 2038 keV, the sum of the energy of the two emitted electrons should show a peak at 2038 keV. In spite of a reduction of the background to effectively zero, such a peak has yet not been seen. The CUORE experiment (Adams *et al.* 2018) studies the neutrinoless decay $^{130}Te \rightarrow {}^{130}Xe$. The Q-value is $Q_{\beta\beta}$ = 2528 keV. CUORE has till now found no peak of the energy sum of the two electrons at 2528 keV. So, the question is still open, if the neutrino is “Dirac” or “Majorana”.

## 4. Majorana Fermions in Solid State Physics

In the last ten years (Elliot, Franz 2015), one could show that Majorana fermions exist also in Solid State Physics, and they promise possible applications for Quantum Computing. In superconductivity one has, at the diffuse Fermi surface, a large number of states depending on the size of the probe of about $10^{20}$. Due to residual interactions, the Fermi Surface is smeared out and one has many quasi-particle excitations of the nature:

$$a_k^+ = u_k\, c_k^+ + v_k\, c_{-k} \qquad\qquad a_{-k} = u_k\, c_{-k} + v_k\, c_k^+$$

At the Fermi energy $k = F$ one has:

$$u_k^2 = v_k^2 = \frac{1}{2}; \qquad\qquad u_k = v_k = \frac{1}{\sqrt{2}}$$

Thus, at the Fermi surface the quasi-particle creation and annihilation operator is the same, or the quasi-particle is equal to the anti-quasi-particle. One has “Majorana fermions”.

The exchange of Majorana fermions produces an additional phase, the winding number. The winding number “zero” and “one” can be used to define the q-bits |0> and |1>:

$$q = \alpha|0> + \beta|1> \qquad\qquad \alpha^2 + \beta^2 = 1$$

The topological (chiral) winding number yields an additional stabilization of the q-bits. Thus, Majorana fermions for superconductors could perhaps serve to make quantum computers more feasible.

## 5. Conclusions

After the return from Heisenberg in Leipzig during August 1933, Ettore Majorana lived secluded till 1937 in an apartment of the Majorana family in Rome. During this time, he did not publish. In 1937 a competition for three new chairs in theoretical physics in the field of the new Quantum Mechanics was opened with Enrico Fermi as chairman of the selection committee. After the short-list was finished, as a surprise, Ettore Majorana applied for one of the chairs. Fermi was convinced that Ettore Majorana was the best candidate of all applicants. But, perhaps, since Giovanni Gentile Jr, the son of a minister of Mussolini, was number three, the short list could not be modified. Enrico Fermi, probably with the help of Giovanni Gentile Sr, succeeded to establish a fourth chair located in Naples for Ettore Majorana. For this competition Ettore had to publish a paper. This is the famous publication in *Il Nuovo Cimento* (Majorana 1937) with the "Majorana neutrino", for which the neutrino is identical to the anti-neutrino. Majorana was appointed in October 1937 to the professorship in Naples, and started with his lectures on the Dirac equation on January 28th, 1938. On March 26th, he disappeared traceless on a trip with the post-ship from Naples to Palermo on the way back to Naples.

The *experimentum crucis* to prove that the neutrino is "Majorana" and not "Dirac" is the neutrinoless double beta decay. Two of the most promising searches for the neutrinoless double beta decay are located in the Gran Sasso underground laboratory (Agostini *et al.* 2018; Adams *et al.* 2018). In spite of heroic efforts, none of the searches for the neutrinoless double beta decay was successful, and thus we do today not know if the neutrino is "Dirac" (different from the anti-neutrino) or "Majorana" (identical with the anti-particle).

At the end, we discussed "Majorana fermions" in Solid State Physics, which can perhaps serve, due to a topological (chiral) winding number, as more stable quantum-bits (q-bits) for quantum computing.

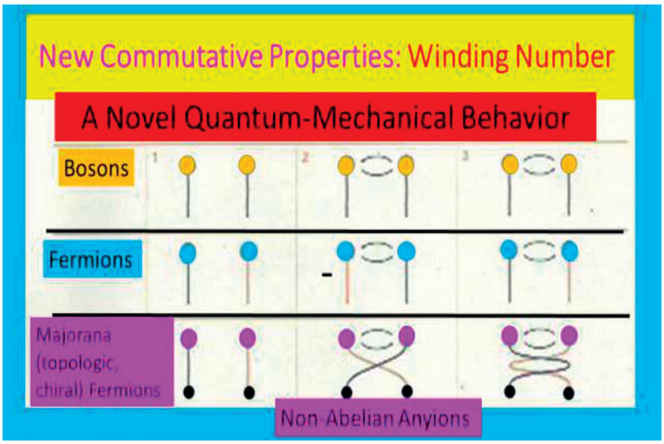


**Fig. 3.** Commutative properties of bosons, fermions and Majorana fermions.

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