Majorana and neutrinos

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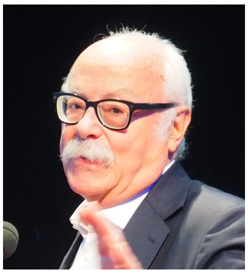


We reconstruct the conceptual trek of Ettore Majorana along the problem of relativistic quantum wave equations. The starting point is given by the strong criticism against Dirac interpretation of the Dirac equation. Majorana does not believe in the existence of negative energy states, neither on the claim that relativistic quantum mechanics implies spin one half elementary particles. Therefore he constructs relativistic wave equations of Dirac type, for any spin, without negative energy states. This is a great achievement. Majorana discovers the unitary infinite dimensional representations of the Lorentz group. For many months, after the discovery of the positron by Anderson in 1932, Majorana does not believe in the new particle. Only in 1933, while in Leipzig, after the experimental confirmation by Blackett and Occhialini, Majorana is obliged to admit that the positron is a really existing new particle. Then he leaves apart the infinite dimensional representations of the Lorentz group, and gives a novel definitive interpretation of the Dirac equation in the frame of relativistic quantum field theory. The resulting scheme is completely symmetric between the electron and the positron. A byproduct of Majorana formulation is the possible interpretation of the neutrino particle as its own antiparticle. Even though surely this research was completed around the year 1933, we have to wait until 1937 to have the paper published on Nuovo Cimento. The reasons of this strange publication strategy is analysed in its academic meaning, in the frame of the foreseen possibility of a new public competition for a Chair in Theoretical Physics in Italy. In our presentation, we will exploit not only the publications of the time, but also the material kept in the archive at the Domus Galilaeana in Pisa, and the letters exchanged by Majorana with other scientists and friends, as for example Emilio Segrè, Giovanni Gentile jr, Quirino Majorana.

1 Introduction

Ettore Majorana (1905-1939) is a famous theoretical physicist, with an intense scientific activity lasting less than a decade. His achievements include notable results in atomic physics, molecular physics, nuclear physics, and elementary particle physics. In Fig. 1, we can see him in a well known picture, but here presented in the right context of his university identification card.

Figure 1 – The university identification card of Ettore Majorana at the Royal University of Rome (Domus Galilaeana, Pisa).

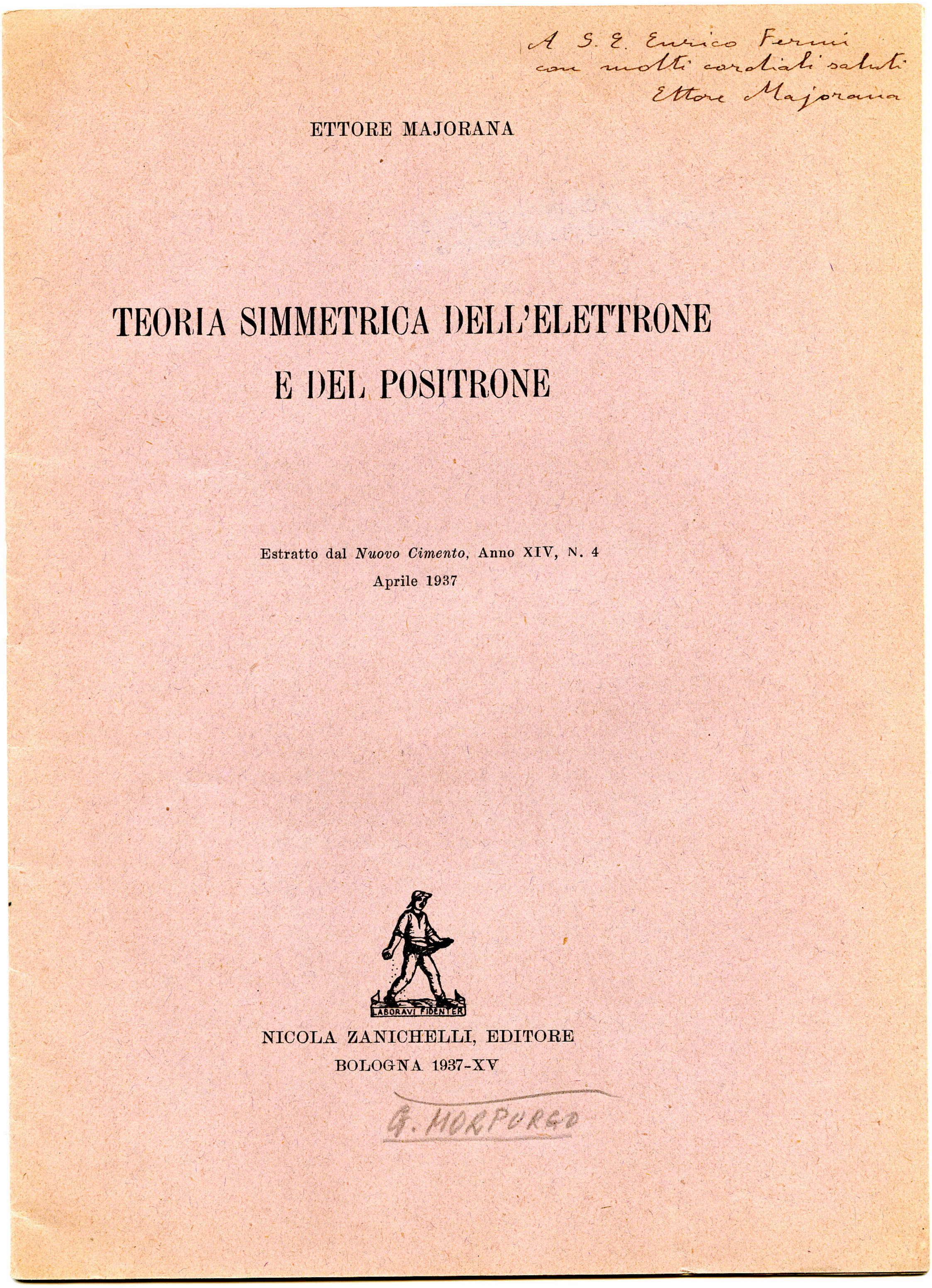
He is mostly known for his sudden disappearence at the end of March 1938, which is almost universally still considered as "mysterious". This fact helped a lot to influence a quite distorted view of his overall personality. We have dedicated to Ettore Majorana the monograph [1], and many research papers, as for example [2]. Our views are summarized in a recent booklet [3], which accompanies the DVD of the movie *Nessuno mi troverà - Majorana memorandum* (*Nobody shall find me - Majorana memorandum*), by the movie director Egidio Eronico.

The scientific, cultural and human personality of Ettore Majorana emerges with a completely new relevance, if the proper primary sources are taken into account, in contrast with the distorted customary views, based on presumed recollections and transmission of episodes by word of mouth. Majorana is a completely normal person, constantly involved in the projection of his normality toward an intellectual and moral excellency, always rich of surprises. He is extremely interested to his academic career, and exercises great efforts to reach important scientific results. His strategy of publication is very efficient. He does not refuse, in various cases, a strong daring intellectual confrontation toward the main exponents of the physical research of the times, as Enrico Fermi, George Gamow, Paul Dirac, Werner Heisenberg. He is able to overcome the inevitable situations of difficulty, as for example after the discovery of the positron, through the adoption of more advanced points of view in his research. Even the institutional and familiar relationships should be considered as normal, by properly taking into account his strong critical attitude.

The involvement of Majorana with the neutrino is witnessed in his last paper [4], by the title *Teoria simmetrica dell'elettrone e del positrone* (*Symmetrical theory of the electron and the positron*), officially published in Nuovo Cimento on April, 1937.

In Fig. 2, we see a reprint with an handwritten dedication:

A S.E. Enrico Fermi
con molti cordiali saluti
Ettore Majorana



A S. E. Enrico Fermi
con molti cordiali saluti
Ettore Majorana

ETTORE MAJORANA

TEORIA SIMMETRICA DELL'ELETTRONE
E DEL POSITRONE

Estratto dal *Nuovo Cimento*, Anno XIV, N. 4
Aprile 1937

LABORAVI FIDENTER

NICOLA ZANICHELLI, EDITORE
BOLOGNA 1937-XV

G. MORPURGO

Figure 2 – A reprint of the 1937 Nuovo Cimento paper with a dedication to Enrico Fermi (courtesy of Giacomo Morpurgo, University of Genova).

The meaning of *S.E.* is *Sua Eccellenza* (*His Excellency*). Enrico Fermi (1901-1954) as a member of the Royal Accademy of Italy was worth of this title by law. The reprint carries the official date of publication.

In the archives, in Pisa and Rome, we have found two identical reprints with the same dedication (without *S.E.* of course): one to Gian Carlo Wick (1909-1992), the other to Giovanni Gentile jr (1906-1942). We do not know whether Giulio Racah (1909-1965) received also a similar gift.

The content of this famous paper is very well known. We will describe the genesis of the paper, and its role for the full professor competition for a chair of Theoretical Physics at the University of Palermo.

In general, we reconstruct the conceptual itinerary followed by Ettore Majorana on the subject of relativistic quantum wave equations, by resorting to original sources, in particular the research notes kept at the Domus Galilaeana in Pisa.

The main points are:

- His strong criticism against the formulation given by Paul Dirac.
- The establishment of the unitary infinite dimensional representations of the Lorentz group.
- The lucid understanding that relativistic quantum wave equations can receive a proper physical interpretation only in the frame of quantum field theory.
- The establishment of the symmetric theory for electrons and positrons.
- Finally the proposal of the Majorana neutrino.

Majorana contributions have great relevance even in the present time, not only for their direct physical contents, as the ongoing research on the Majorana neutrino shows, but also for their methodological strength and originality.

Our treatment here will be very short and schematic. A more extended version will be presented elsewhere. The scientific and academic life of Ettore Majorana is extensively described in [1].

As a matter of fact, the period when Majorana is involved on relativistic wave equations is quite short (essentially 1932-1933), even though the final paper on Majorana neutrino is published after many years in 1937, on occasion of the participation to the competition for a chair in Theoretical Physics at the University of Palermo.

2 Dirac equation

It is very well known that Dirac theory originates from a relativistic generalisation of the quantum mechanical Schrödinger equation.

The relativistic particle is described through a four component wave equation $\psi_a(\mathbf{x}, t)$. In a given reference frame, time evolution is ruled by the wave equation

$$i\hbar\partial_t\psi = H\psi, \tag{1}$$

where the Hamiltonian is given by

$$H = c\alpha \cdot \mathbf{p} + \beta mc^2. \tag{2}$$

Here the momentum is $\mathbf{p} = -i\hbar\nabla$, according to Heisenberg and Schrödinger, while the matrices $\alpha = (\alpha_1, \alpha_2, \alpha_3)$ and β, have the well known expression given by Dirac. Dirac particles have spin 1/2.

The theory is relativistically invariant. If the four vector of the space-time coordinates $x = (\mathbf{x}, ct)$ transforms according to $x \to x' = \Lambda x$, under a Lorentz transformation, then there exist a transformation $\psi \to \psi'$ defined by

$$\psi'(x') = U(\Lambda)\psi(x), \tag{3}$$

with a suitable matrix $U(\Lambda)$, in such a way that ψ' satisfies the same wave equation in the new reference frame.

The Dirac particle is immediately identified with the electron, with the right spin and magnetic momentum properties.

There is a weak point in the theory, but this is at the same time a reason of strength. There are negative energy states. In fact, we have $\beta = diag(1, 1, -1, -1)$. In the reference frame where the particle is at rest, $\mathbf{p} = 0$, the energy is $H = \beta mc^2$, with two eigenvalues $\pm mc^2$.

Negative energy states are at the time a real difficulty for the Dirac equation, as they can give rise to many paradoxical phenomena.

It is very well known the way exploited by Dirac in order to overrun the difficulties. In the celebrated picture of the Dirac sea, all negative energy states are occupied, according to Pauli principle. A hole in the sea can be interpreted as a positive charge particle. In the initial stage, and for a long period, the positive charge hole is recognised as the proton.

In order to understand the reasons of Majorana criticism, let us consider the Dirac paper [5], by the title *A Theory of Electrons and Protons*, published on January 1^{st} 1930, and read some sentences on page 363, whose essential content is well surviving for example even in the 1931 french edition of his book *Principles of quantum mechanics* (first english edition May 29, 1930).

Dirac writes: “In the X-ray case the holes should be counted as things of negative energy, since to make one of them disappear (*i.e.*, to fill it up), one must add to it an ordinary electron of positive energy. Just the contrary holds, however, for the holes in our distribution of negative-energy electrons. These holes will be things of positive energy and will therefore be in this respect like ordinary particles. Further, the motion of one of these holes in an external electromagnetic field will be the same as that of the negative-energy electron that would fill it, and will thus corresponding to its possessing a charge $+e$. We are therefore led to the assumption that *the holes in the distribution of negative-energy electrons are the protons.* When an electron of positive energy drops into a hole and fills it up, we have an electron and proton disappearing together with emission of radiation.”

The last two sentences are really astonishing. As a matter of fact, in these first attempts of interpretation of the sea of fully occupied negative-energy electrons, Dirac is sure of having constructed a “symmetrical theory of electrons and protons”, as explicitely declared in one of the chapters of the first edition of his book.

Moreover, the whole treatment based on the Dirac equation leads to the idea that the spin 1/2 for the particle is a necessary consequence of quantum mechanics and relativity.

It is very well known that further developments led to the result that the hole in the sea must have the same mass of the electron. It is a kind of anti-electron (Dirac, May 1931), later called positron. From the encounter of the electron and the hole, the electron can be absorbed in the sea. Both disappears, and the energy is recovered in the form of a couple of photons. On the other hand, a photon with sufficiently high energy, passing near a nucleus, can disappear and transfer an electron of the sea from a negative energy state to a positive one. In this way a couple of real particles electron-hole is created. The nucleus is necessary in order to absorb the excess of momentum.

The theory of the Dirac sea has enormous potentialities in the physical interpretation. The result is a great strength for the Dirac equation: in a sense it “predicts” the existence of the positron.

3 Majorana criticism

It is expressed with the typical Majorana sharp style (congruent with his traditional image as the Great Inquisitor) in the paper [6] by the title *Teoria relativistica di particelle con momento intrinseco arbitrario* (*Relativistic theory of particles with arbitrary intrinsic momentum*).

About the Dirac equation, firstly he says: “poiché questa è applicabile solo a particelle con momento intrinseco $s = 1/2$, ho cercato equazioni analoghe nella forma a quelle di Dirac, sebbene alquanto più complicate, le quali permettono la considerazione di particelle con momento intrinseco arbitrario, e in particolare nullo.” (“Since this equation applies only to particles with intrinsic momentum 1/2, I searched for equations analogous to Dirac one, albeit somewhat more complicated, which allow to consider particles with arbitrary spin, in particular null”).

Moreover, he remarks that “l’indeterminazione nel segno dell’energia può essere in realtà superata, usando equazioni del tipo fondamentale, solo se la funzione d’onda ha infinite componenti che *non* si lasciano spezzare in tensori o spinori finiti.” (“as a matter of fact the indeterminacy in the sign of the energy can be avoided, by exploiting equations of the basic type, only if the wave function has an infinite number of components, which can *not* be split in finite tensors or spinors”).

Therefore, he arrives to a very important discovery. By using infinite component wave equations, it is possible to recover relativistic invariance in a formulation where the β matrix has only positive eigenvalues.

The corresponding Lorentz transformations on the wave function turn out to be unitary. In his 1932 paper, Majorana gives the explicit expression of the generators in the particular case, where some invariant of the representation is null. However he claims that “more general infinite dimensional tensors or spinors can be defined for any value of the invariant”. In fact, at the Domus Galilaeana in Pisa, we can find personal research notes, where the explicit expressions of the generators are given in the general case.

In conclusion, in 1932 Ettore Majorana gives all unitary infinite dimensional representations of the Lorentz group. It is a great mathematical discovery, very important also from the physical point of view. Majorana theory applies to particles with any spin. No negative energy states appear.

His pioneering role is fully recognised in the majestic 1939 paper by Eugene Wigner on Annals of Mathematics[7], where all representations are constructed through elegant group theory methods.

The 1932 paper on Nuovo Cimento is considered by Majorana as a preliminary announcement of his results.

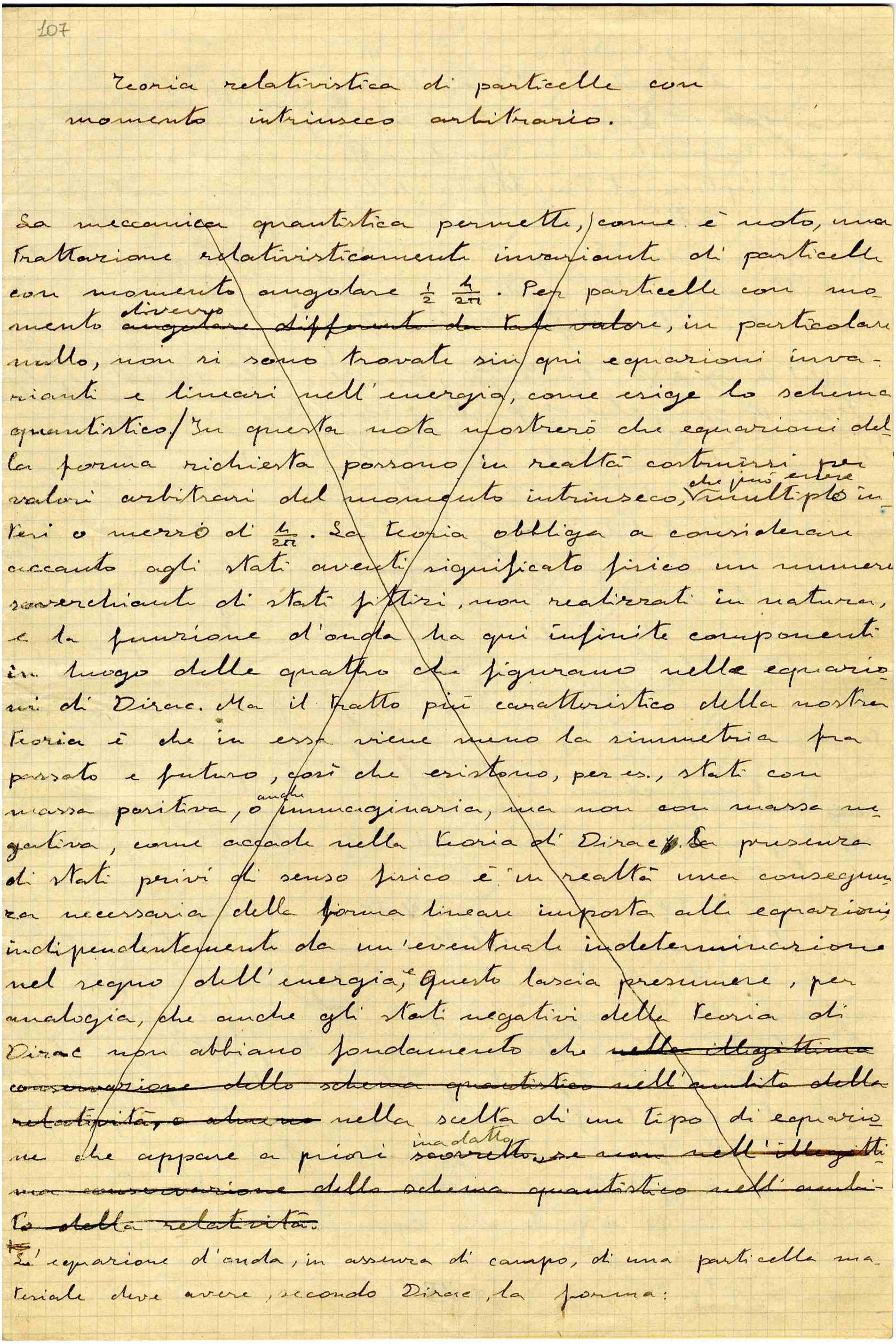
The original handwritten manuscript is kept at the Domus Galilaeana in Pisa (11 pages). The final wording is reached after extensive and substantial cancellation and rewriting. Clearly the argument is completely new and difficult. In the erased parts there is also mention about the time-reversal invariance, not preserved in the published version.

To give a flavor of Majorana style, let us read for example a sentence, carefully written in a first moment and then cancelled, concerning the appearance of negative energy states: *Si è perfino tentato, non senza ardimento, di attribuire realtà fisica agli stati negativi, come se la natura fosse in imbarazzo per la scelta del segno del radicale* $\sqrt{m^2c^4 + c^2p^2}$. (*There has been even the attempt, not devoid of temerity, to give physical reality to negative states, just as if the nature would be embarrassed concerning the choice of the sign in the radical* $\sqrt{m^2c^4 + c^2p^2}$.)

It is possible to follow in complete detail the progress in the formulation of the paper, by reconstructing the various versions, through the subsequent cancellations and additions.

In Fig. 3 we see one page of the manuscript, characterized by extensive cancellations.

According to the Majorana careful strategy of publication, a conclusive paper was planned to be sent to the prestigious german journal Zeitschrift für Physik. In a January 21 (1933) letter to Ugo Bordoni, high officer in the National Council of Researches, the agency supporting his fellowship in Germany, Majorana, just arrived in Leipzig, writes: *Attendo attualmente alla*



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Teoria relativistica di particelle con momento intrinseco arbitrario.

La meccanica quantistica permette, come è noto, una trattazione relativisticamente invariante di particelle con momento angolare $\frac{1}{2}\frac{h}{2\pi}$. Per particelle con momento diverso ~~angolare differente da tale valore~~, in particolare nullo, non si sono trovate sin qui equazioni invarianti e lineari nell'energia, come esige lo schema quantistico. In questa nota mostrerò che equazioni della forma richiesta possono in realtà costruirsi per valori arbitrari del momento intrinseco, che può essere multiplo intero o mezzo di $\frac{h}{2\pi}$. La teoria obbliga a considerare accanto agli stati aventi significato fisico un numero soverchiante di stati fittizi, non realizzati in natura, e la funzione d'onda ha qui infinite componenti in luogo delle quattro che figurano nelle equazioni di Dirac. Ma il fatto più caratteristico della nostra teoria è che in essa viene meno la simmetria fra passato e futuro, così che esistono, per es., stati con massa positiva, o anche immaginaria, ma non con massa negativa, come accade nella teoria di Dirac. La presenza di stati privi di senso fisico è in realtà una conseguenza necessaria della forma lineare imposta alle equazioni, indipendentemente da un'eventuale indeterminazione nel segno dell'energia. Questo lascia presumere, per analogia, che anche gli stati negativi della teoria di Dirac non abbiano fondamento che ~~nella illegittima conservazione dello schema quantistico nell'ambito della relatività, o almeno~~ nella scelta di un tipo di equazione che appare a priori inadatto ~~scorretto, se non nell'illegittima conservazione dello schema quantistico nell'ambito della relatività.~~

L'equazione d'onda, in assenza di campo, di una particella materiale deve avere, secondo Dirac, la forma:

Figure 3 – One page of the original manuscript of the 1932 Nuovo Cimento paper (Domus Galilaeana, Pisa).

elaborazione di una teoria relativistica per la descrizione di particelle con momento intrinseco arbitrario che ho iniziata in Italia e di cui ho dato notizia sommaria nel Nuovo Cimento (in corso di stampa). (*I am here now involved in the elaboration of a relativistic theory for particles with arbitrary intrinsic momentum, initiated in Italy, about which I have given concise notice in Nuovo Cimento (in press)*).

While on the following letter of March 3, we find: *Ho inviato alla Zeitschrift für Physik un articolo sulla teoria dei nuclei. Ho pronto il manoscritto di una nuova teoria relativistica delle particelle elementari e lo invierò alla stessa rivista fra qualche giorno.* (*I have sent to Zeitschrift für Physik a paper on the theory of nuclei. I have ready the manuscript of a new elementary particle theory, which will be sent to the same journal in few days*).

Unfortunately, this paper, fully finished, will never appear. The manuscript does not exist among the Majorana material in Pisa, nor in the Family archive.

However, it is clear that until March 1933 Majorana does not believe in the existence of the positron. Hence his refusal of the Dirac equation. In a letter to Giovanni Gentile jr (February 1933), Majorana says that nobody in Leipzig believes in the positron. The first experimental evidence, obtained by C. Anderson with a cloud chamber in 1932 [8], can be easily interpreted as electrons going in the opposite direction. Majorana says that this is also the opinion of Rutherford.

However, the 1933 experiments by Blackett and Occhialini [9], exploiting a cloud chamber controlled by Geiger-Müller counters in coincidence, dissolve any doubt. The conviction of the physical existence of the positron is rapidly spreading out. In a letter to Emilio Segrè (May 22, 1933), whose original is kept in the Bancroft Library in Berkeley, Majorana communicates the *novità di stagione* (*season news*) that in Leipzig the Dirac theory of negative electrons is gaining credit. Heisenberg is seriously involved in research on the subject.

The discovery of the positron gives more strength to Dirac scheme, and Majorana now does not feel as urgent the publication of his extended paper on the equations for particles with general spin. This is a reasonable explanation, based on solid physical reasons, for the missed publication of the paper.

The definite confirmation of the physical existence of the positron is a triumph for Dirac equation. Lord Rutherford, as an extraordinary experimental Physicist, shows regret about the fact that the positron has been foreseen theoretically, before being seen experimentally.

The Nobel Prize in Physics 1933 was awarded jointly to Erwin Schrödinger and Paul Adrien Maurice Dirac "for the discovery of new productive forms of atomic theory" (official Nobel motivation).

In the presentation speech, the Chairman of the Nobel Committee says: "Dirac has set up a wave mechanics which starts from the most general conditions. From the start he put forward the requirement that the postulate of the relativity theory be fulfilled. Viewed from this general formulation of the problems it appeared that the self-rotation of the electron which had previously come into the theory as an hypothesis stipulated by experimental facts, now appeared as a result of the general theory of Dirac.

Dirac divided the initial wave equation into two simpler ones, each providing solutions independently. It now appeared that one of the solution systems required the existence of positive electrons having the same mass and charge as the known negative electrons. This initially posed considerable difficulty for Dirac's theory, since positively charged particles were known only in the form of the heavy atom nucleus. This difficulty which at first opposed the theory has now become a brilliant confirmation of its validity. For later on, positive electrons, the positrons, whose existence was stipulated in Dirac's theoretical investigation, have been found by experiment."

4 The symmetrical theory of electron and positron

After the delusion following the discovery of the positron, Majorana continues his research on the relativistic formulation of elementary particle theory, in the frame of the new emerging physical frame.

In a 1936 letter to the uncle Quirino he declares that he is working on quantum electrodynamics. Moreover, he gives the title "Quantum Electrodynamics" to his proposed program for a projected free course at the University of Rome, in the a.y. 1936-1937. Among the arguments we surprisingly find: *The quantization of the Maxwell-Dirac equations. Study of the relativistic invariance. The positive electron and the symmetry of charges.*

While clearly the results were obtained many years before, it is only in 1937 that the fundamental paper appears [4].

Only four pages of the original manuscript survive in the Majorana Archive in Pisa. The text is identical to the published version. Where are the other pages?

In Fig. 4 we can see one of the surviving pages.

This is a really fascinating paper, devoted to interacting quantum field theory of electron-positron-photon (quantum electrodynamics). The equation of motion are derived through a very elegant variational principle for noncommuting fields.

From a conceptual point of view there are two essential ingredients.

First of all it is recognised that relativistic wave equations can have a consistent physical interpretation only in the frame of a quantum field theory. Field equations rule the time evolution not for the quantum wave function, as in the nonrelativistic case of Schrödinger equation, but for quantum field operators, which in the noninteracting case can be split in two pieces, one related to particle creation, and the other related to particle annihilation.

In particular, Dirac equation gets its consistent physical interpretation, where there is no place for the Dirac sea.

Here we notice that in the Amaldi Archive at the Department of Physics in Rome there is a recollection by the distinguished theoretical physicist Gian Carlo Wick, who communicates that Majorana was aware of the correct interpretation of the Klein-Gordon equation (spin zero) in the frame of quantum field theory at least since 1931, the year of the Rome nuclear physics conference. According to this recollection Majorana anticipates of many years the 1934 results of Pauli-Weisskopf.

The second fundamental ingredient is given by the well known Majorana representation for Dirac matrices. Dirac and Majorana choices are physically equivalent, but Majorana representation allows to define separately the electronic and the positronic field. Hence a completely symmetrical treatment for the two particles, as shown in the title of the paper, which clearly resonates critically with the Dirac expression "symmetrical theory of electron and proton" of some years before.

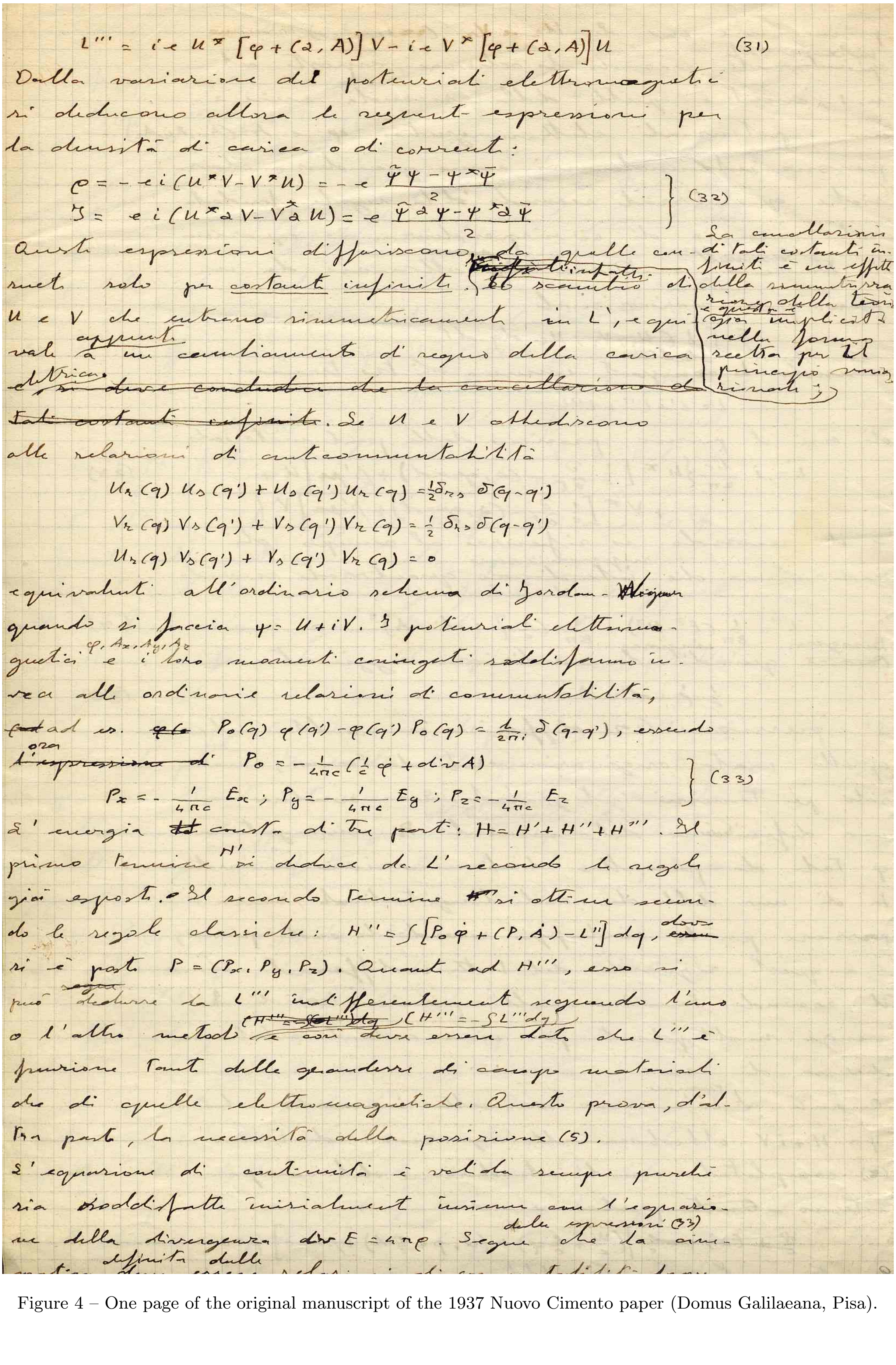
Majorana representation allows also to introduce a "new description for neutral particles (neutron and neutrino)", where particle and antiparticle coincide.

The neutron is obviously excluded (magnetic momentum, and later baryonic number). Therefore we are left with the possibility that the neutrino, already introduced in the 1933-34 papers of Fermi on beta decay, is a Majorana particle. This is the subject of intense contemporary research, as shown for example by the contribution of S. Petcov [10].

It should be remarked that Majorana representation for the Dirac matrices, is already contained in Dirac paper, and exploited by him to prove that the complex conjugate of the wave function for a positive energy state is the wave function of a negative energy state.

But Majorana extends these considerations in his quantum field theoretical frame, reaching two important results: the symmetric theory for the electron and the positron, and the possibility for the existence of a neutral particle identical to its own antiparticle.

Majorana neutrino is largely treated in many contributions to this Volume, in all its connections with condensed matter physics, and cosmological problems.



$$L''' = ieU^*[\varphi + (\alpha, A)]V - ieV^*[\varphi + (\alpha, A)]U \quad (31)$$

Dalla variazione dei potenziali elettromagnetici si deducono allora le seguenti espressioni per la densità di carica e di corrente:

$$\rho = -ei(U^*V - V^*U) = -e\frac{\tilde{\Psi}\Psi - \Psi^*\bar{\Psi}}{2}$$
$$J = ei(U^*\alpha V - V^*\alpha U) = e\frac{\tilde{\Psi}\alpha\Psi - \Psi^*\alpha\bar{\Psi}}{2} \quad (32)$$

Queste espressioni differiscono da quelle consuete solo per costanti infinite. ~~Infatti~~ Infatti lo scambio di U e V che entrano simmetricamente in L', equivale appunto a un cambiamento di segno della carica elettrica. ~~e si deve concludere che la cancellazione di tali costanti infinite~~. Se U e V obbediscono alle relazioni di anticommutabilità

(La cancellazione di tali costanti infinite è in effetto della simmetrizzazione della teoria e questa è implicita nella forma scelta per il principio variazionale;)

$$U_r(q)U_s(q') + U_s(q')U_r(q) = \tfrac{1}{2}\delta_{rs}\delta(q-q')$$
$$V_r(q)V_s(q') + V_s(q')V_r(q) = \tfrac{1}{2}\delta_{rs}\delta(q-q')$$
$$U_r(q)V_s(q') + V_s(q')V_r(q) = 0$$

equivalenti all'ordinario schema di Jordan-Wigner quando si faccia $\Psi = U + iV$. I potenziali elettromagnetici φ, A_x, A_y, A_z e i loro momenti coniugati soddisfanno invece alle ordinarie relazioni di commutabilità, ad es. $P_0(q)\varphi(q') - \varphi(q')P_0(q) = \frac{h}{2\pi i}\delta(q-q')$, essendo ora ~~l'espressione di~~

$$P_0 = -\frac{1}{4\pi c}\left(\frac{1}{c}\dot{\varphi} + \mathrm{div} A\right)$$
$$P_x = -\frac{1}{4\pi c}E_x;\ P_y = -\frac{1}{4\pi c}E_y;\ P_z = -\frac{1}{4\pi c}E_z \quad (33)$$

L'energia consta di tre parti: $H = H' + H'' + H'''$. Il primo termine H' si deduce da L' secondo le regole già esposte. Il secondo termine H'' si ottiene secondo le regole classiche: $H'' = \int[P_0\dot{\varphi} + (P, \dot{A}) - L'']dq$, dove si è posto $P = (P_x, P_y, P_z)$. Quanto ad H''', esso si può dedurre da L''' indifferentemente seguendo l'uno o l'altro metodo ($H''' = -\int L''' dq$) ~~e così deve essere dato che L''' è~~ funzione tanto delle grandezze di campo materiali che di quelle elettromagnetiche. Questo prova, d'altra parte, la necessità della posizione (5).

L'equazione di continuità è valida sempre purchè sia soddisfatta inizialmente insieme con l'equazione della divergenza $\mathrm{div} E = 4\pi\rho$. Segue che la cinematica definita dalle espressioni (33) delle relazioni di commutabilità ...

Figure 4 – One page of the original manuscript of the 1937 Nuovo Cimento paper (Domus Galilaeana, Pisa).

In conclusion, we see that Ettore Majorana is also remarkable for the lucid methodological procedures exploited in his research, where phenomenological considerations, based on physical intuition, are blended with advanced mathematical methods, relying on symmetry and group theory.

Let us finish this Section with the following considerations. There are no doubts that it was Enrico Fermi who proposed the name "neutrino" (in Italian "the neutral small one"), as recalled by Wolfgang Pauli in a comment to the talk by Heisenberg at the Solvay meeting in October 1933 [11]: "Pour le distinguer des neutrons lourds, M. Fermi a proposé le nom 'neutrino'." It is only in italian that the name "neutrone" carries also an apparent meaning of being big, while "neutrino" carries the opposite diminutive meaning. Thus Fermi did invent the term "neutrino" by working on the opposition between "neutrone" ("the big neutral object", discovered by Chadwick in 1932) and "neutrino" ("the small neutral object", introduced by Pauli in 1930). It should also be remarked that the original name devised by Pauli was "neutron", and Fermi used this word still during his invited contribution at the *Congrès International d'Électricité* held in Paris in the Spring of 1932, by pointing out that one should distinguish between the Chadwick neutron and the Pauli neutron, in order to avoid any confusion. Therefore the coinage of the term "neutrino" by Fermi took shape in the interval between the Spring of 1932 (the Paris Conference) and the Fall of 1933 (the Solvay meeting).

5 The timing of the paper

Ettore Majorana was not very lucky in his academic career. After earning his doctoral degree in Physics (*Laurea in Fisica summa cum laude*) in 1929, he was not offered any position at the Institute of Physics in via Panisperna, in contrast to all other young "via Panisperna boys" (Emilio Segrè, Edoardo Amaldi, Gian Carlo Wick). He earned his "libera docenza" in 1932, a title enabling to give a free course at the university, but was never put in condition to really give a course. Majorana was surely outside the adopted plan of development of the Institute in via Panisperna.

However, in 1933 he was given a fellowship by the National Council of Researches, and went to Leipzig, at the Heisenberg Institute, to work on the theory of nuclei, where he developed the very successful Majorana exchange forces among proton and neutron. After the trip abroad Majorana did not publish anything since the last paper in March 1933.

In 1936 the rumor spread that the University of Palermo could call for a national competition for a Chair in Theoretical Physics. The last one in Italy was held in 1926, when Enrico Fermi was called to Rome.

In order to understand the events, it is necessary to recall the rules. Some University asks for a competion to some Chair. The Minister, through his counsellors, checks that there are good cultural and scientific reasons, and the existence of financial support in the State budget. Then issues an official public call on the State official Gazette. The candidates have some months to submit their claims, before a definite deadline. Then the appointing committee is nominated by the Minister. After a careful perusal of the presented documents, the Committe choses three winners in a given order. The first in the list is called at the Faculty where the competition was asked, the others in other Faculties, according to the possibilities.

The competition is by titles only, essentially given by the scientific publications. Winners can be easily foreseen.

The official call for the Palermo competition was issued in March 15, 1937. The deadline for candidate application was June 15, 1937.

Since Majorana stopped publication in 1933, he was not a reasonable candidate, as devoid of scientific continuity in his activity.

The other possible and sure candidates were Gian Carlo Wick, Giulio Racah, and Giovanni Gentile jr, here listed in the obvious order, according to the objective strength of their scientific curriculum at the time. As a matter of fact, Emilio Segrè, the professor of Experimental Physics in Palermo, had already taken contacts with Wick, the sure first winner, in order to have him in the Faculty. Also Racah and Gentile were in contact with the Faculties in Florence and Milan, respectively.

But Majorana shows a deep and subtle knowledge of academic practice. Just AFTER the official call on the Gazette (March 15) he submits to Nuovo Cimento his paper on the symmetric theory, which is published in April BEFORE the deadline (June 15), and can be presented to the competition.

By a magic timing, Majorana, who can not be a reasonable candidate before March 15, becames automatically the first among the others before the deadline of June 15. In fact, his last paper, added to the previous remarkable ones, makes him the candidate with the best curriculum.

The timing is very strict. To publish the paper before the official call of the competition was in a sense dangerous. In this case, Majorana would have been the sure first winner, with the plans of Palermo and Milan seriously upset, the last candidate being thrown out of the winning triplet. Taking into account the sure complete failure of the previously established general academic planning at the national level, the Minister, well in the frame of his absolute powers, could have decided to not issue the official call on the Gazette, by resorting to some "administrative reason".

Even the reported "strange" behavior of Majorana in the months before (long hair, living at home, refusing correspondence, ...) could be interpreted as reinforcing the idea that he was completely out of the academic world.

At this point, with the proper timing, it seemed that Majorana would reach his objective to become Professor in native Sicily, as many members of his Family were, but it was not so. The powerful academic Authorities could not accept a drastic change in the planning, due to some external "perturbation".

The Committee, chaired by Enrico Fermi of course, recognized the outstanding scientific status of Majorana, well superior to the other candidates, and declared to hesitate to apply the normal rules of the competition (comparison between candidates), by suggesting the Minister to nominate Majorana as Professor in some University of the Kingdom, outside of the frame of the competition.

The Minister immediately nominated Majorana as full Professor at the University of Naples. Therefore, Majorana was in any case eliminated from the competition, and sent to exile in Naples. He disappeared after few months in March 1938.

The three natural winners, Wick, Racah and Gentile, were called in the three Universities of Palermo, Florence and Milan, according to the established planning.

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