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Ettore Majorana's degree thesis

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Summary. — A short account is given of Majorana degree thesis, closely following his Communication at XXVIII Congress of the Italian Physical Society in 1928.

1. – Introduction

Ettore Majorana's university studies show some peculiar aspects of extreme interest(1). After obtaining his high school diploma in 1923 he enrolled in the two-year preparatory course for Aspiring Engineers at the Faculty of Science of the University of Rome, easily passing all the examinations foreseen and obtaining the relative diploma. He then enrolled in the Engineering School of Application, passing all the examinations in the first two years. At the end of 1927 we have a serious diversion. Majorana stopped attending the Engineering courses, but carefully prepared his passage to the Physics degree course.

In particular, in 1928 he passed his Theoretical Physics exam with Fermi, still as a student enrolled in Engineering, and was involved in intense and original research into Fermi's statistical model for atoms and molecules. At the end of 1928, he officially obtained a transfer to the Faculty of Science. He easily passed the remaining exams and graduated in Physics with honours on 5 July 1929, surprisingly with a degree thesis on Nuclear Physics. We analyse in detail some aspects of his degree that are in fact a real "Majorana mystery" *ante litteram*. Indeed, the subject of the thesis does not repeat the contents of his previous brilliant research in the statistical model of the atom, but a completely new argument was attacked, Nuclear Physics.

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(1) A copy of Majorana's thesis work is at Domus Galilaeana in Pisa (Italy).

2. – The contents of the thesis

Majorana graduated on 6 July 1929, with a thesis in Nuclear Physics, on alpha decay, under the guidance of Enrico Fermi [1,2]. Both Majorana, as thesis student, and Fermi as supervisor, were at their first experience in the field of Nuclear Physics. This is also the first time that research in this field has been carried out in Italy. Recently, Majorana's thesis has attracted the attention of some scholars because of its scientific content, so much so that it has been called "the graduation thesis of a brilliant mind" [3].

However, in further analysing the text of Ettore Majorana's thesis, and the circumstances of its appearance, it is possible to note some significant anomalies. Let us remember that in 1928 (one year before the thesis) Majorana was involved in an intense research activity in Theoretical Physics, still as an engineering student: in particular on the statistical model of the atom, introduced by Fermi, in December 1927, only a few months before, the so-called "Thomas-Fermi atom".

From Ettore Majorana's notebooks kept at the Domus Galilaeana in Pisa, we can see that Majorana's interest in this subject dates back to early 1928.

After an initial outlet in an article in collaboration with Giovanni Gentile jr., presented at the Accademia dei Lincei by O. M. Corbino on 24 July 1928 (note that on 7 July 1928 Majorana took the Theoretical Physics examination with Fermi) and published in the *Rendiconti dell'Accademia* [4], Majorana, still in 1928, continued his research on the statistical model on his own, arriving in particular at an improvement of Fermi's approach (he modified the expression of the effective potential acting on the optical electron), at its extension to the case of positive ions (which is the firstly made treatment) and at interesting applications on the shift of the Roentgen spectral lines of some elements when they take part in oxygen compounds. The results of this intense research activity were communicated by Majorana at the XXII General Meeting of the Italian Physical Society (S.I.F.), held in Rome from 28 to 30 December 1928.

This communication was then published in *Il Nuovo Cimento* [5] which is the Society's journal, with the title "Research for a general expression of Rydberg corrections, valid for neutral or positively ionised atoms". This Majorana's Communication has never been cited by Fermi, who eventually, in 1934, will adopt Majorana procedure [6], and not even by those who have dealt with Majorana. A first account was given by us, immediately after we discovered it in *Il Nuovo Cimento*, in 2008 [2, 7].

It should be noted that Majorana's Communication is a testimony not only to the remarkable results achieved, but also to the confidence and determination of Majorana (a 4th year Physics student) to make his results known. It is nothewortyhy that O. M. Corbino, T. Levi Civita, V. Volterra, G. Polvani, Q. Majorana, A. Carrelli, E. Fermi, and many other illustrious people were present. Also in 1928 Majorana obtained other original results on the statistical model of the atom, which can be found in the notebooks of the Domus Galilaeana.

Majorana's communication concludes as follows: "The author thanks Prof. Fermi for his advice and suggestions concerning the new applications of the statistical method that have shed so much light on atomic physics and whose fruitfulness, far from being exhausted, is still waiting to be tested in broader and more promising fields of investigation".

Considering these remarks, one would have expected Majorana to continue his research on the statistical model of the atom, or at least that his thesis, still to be defined (let us remember that he had just enrolled in the fourth year of Physics), would concern this subject.

Instead, there is an unforeseeable fracture. In essence, Majorana seems to completely lose the fruits of a year's work: he does not publish in an extended form either the results communicated to Congress or the other results obtained, on the contrary he stops working on the statistical model of the atom altogether.

It is probable that he realised, or someone made him realise, that it was not appropriate, at this point in his career, given the results he had achieved that were in opposition to Fermi's, for him to be involved in a clash on scientific issues with one of the greatest existing theoretical physicists, and in addition his own supervisor.

As a matter of fact, the results communicated at the Congress in Rome, together with those outlined in the notes in the notebooks, if duly developed and published, would have made the young Majorana a fierce competitor of the already established Fermi, not only in relation to the foundations of the statistical model of the atom, but also to the effects of future applications in broader and more promising fields of investigation.

In fact, at the beginning of July the following year, Majorana graduated in Physics with a dissertation on a completely different subject, tackling, in a very short time, problems in Nuclear Physics, which was at that time the most advanced frontier of scientific research in Physics. The title of the submitted thesis (or "Dissertation", as it was then called) was "Sulla meccanica dei nuclei radioattivi" (On the Mechanics of Radioative Nuclei).

The graduation session, according to the relative minutes, took place on 6 July 1929, chaired by Corbino in the presence of, among others, Lo Surdo, Fermi, Volterra, Levi Civita and Trabacchi.

As required by the regulations, Majorana also presented three "oral theses", respectively: "On a photoelectric effect observed in audions" (Advanced Physics), "On the equilibrium configurations of a rotating fluid" (Mathematical Physics), "On statistical correlations" (Probability Calculus).

He graduated with 110/110 *cum laude*. The thesis advisor was Enrico Fermi.

3. – Majorana at work

Majorana began the work that would lead to his thesis, presumably in early 1929.

At that time Nuclear Physics was a completely new subject compared to the lines of research that had been carried out up to that time in Rome and, more generally, in Italy. These, in fact, essentially concerned either Classical Physics or Quantum Mechanics applied to the atom, in relation to Spectroscopy, Statistics and, more recently, electromagnetic radiation.

The only exception is an extremely critical note by Giovanni Gentile jr. of February 1928 [8] concerning a classical model of nucleus, which Rutherford had proposed the year before to explain natural alpha-type radioactive decay in Classical Physics; Majorana's thesis also concerns alpha decay, but from a completely new and extremely topical perspective, that of Quantum Mechanics.

Majorana took his starting point from a recent meeting held under the title "Discussion on the Structure of Atomic Nuclei", at the Royal Society in London, opened by Rutherford on 7 February 1929 [9] (the Proceedings would be published on 6 April 1929) in which the latest results in this field were outlined and in which George Gamow, among others, took part.

Gamow, a Soviet nuclear physicist with deep ties in the West, in the summer of 1928, only a few months before Majorana's thesis, had succeeded in explaining alpha decay

within the framework of the New Physics, by assuming a brilliant mechanism based on the quantum mechanical tunnel effect [10].

As is well known, the tunnel effect involves the possibility of a particle escaping, with certain probabilities, from a region in which it is trapped by a potential barrier.

A theory similar to Gamow's from a physical point of view was independently developed around the same time by the American physicists R. W. Gurney and E. U. Condon. However, while Gamow's article, published in *Zeitschrift für Physik* in March 1928, contains the complete analysis of the problem, Gurney and Condon's article [11], submitted to *Nature* magazine on 30 July 1928 and published in expanded form in *Physical Review* on 1 February 1929 [12], only gives a brief summary of the theory.

One of the immediate reactions to Gamow's first article is that of von Laue [13], published on 11 December 1928 in *Zeitschrift für Physik*, who, after recognising that the quantum theory of the atomic nucleus outlined by Gurney and Condon and firstly developed by Gamow is to be regarded as the "finest result of the New Physics", observes dramatically "But in Gamow's analysis the Mathematics is not completely in order".

Further criticism of Gamow's article was also made in February 1929 by the Hungarian physicist Kudar in three articles in *Zeitschrift für Physik* [14]. Gamow's second article of 1928, together with Gamow's and Houtermanns' article, Laue's article, and Kudar's three articles are Majorana's starting point in his thesis, as can be seen from his bibliography, in which, strangely enough, he does not quote Gamow's first article of March 1928, on which the thesis is precisely centred (fig. 1).

The thesis is very short. It consists of 47 typewritten pages, plus two pages —the Heading and the Bibliography— handwritten by Majorana. All formulas and some corrections to the typescript are also handwritten by Majorana (fig. 2).

4. – Two manuscripts

A text very similar to the thesis, which we could call the "thesis manuscript", is found in a notebook by Majorana, called notebook No. 10 (fig. 3).

This text consists of four "chapters" (which we find again with the same title and a slightly different content in the thesis) entitled respectively: I) Spontaneous ionisation of a hydrogen atom placed in a region of negative potential (pp. 1–15); II) The fundamental law of radioactive phenomena (pp. 18–26); III) Collision of an α particle against a radioactive nucleus (pp. 30–43); IV) The calculations of Gamow and Houtermans (pp. 44–52).

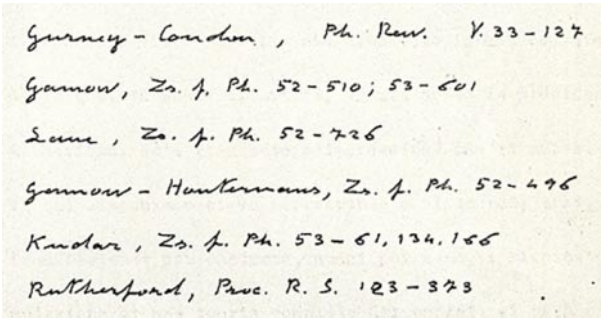

Fig. 1. – Majorana thesis's references ("Majorana Archive", Domus Galilaeana, Pisa).

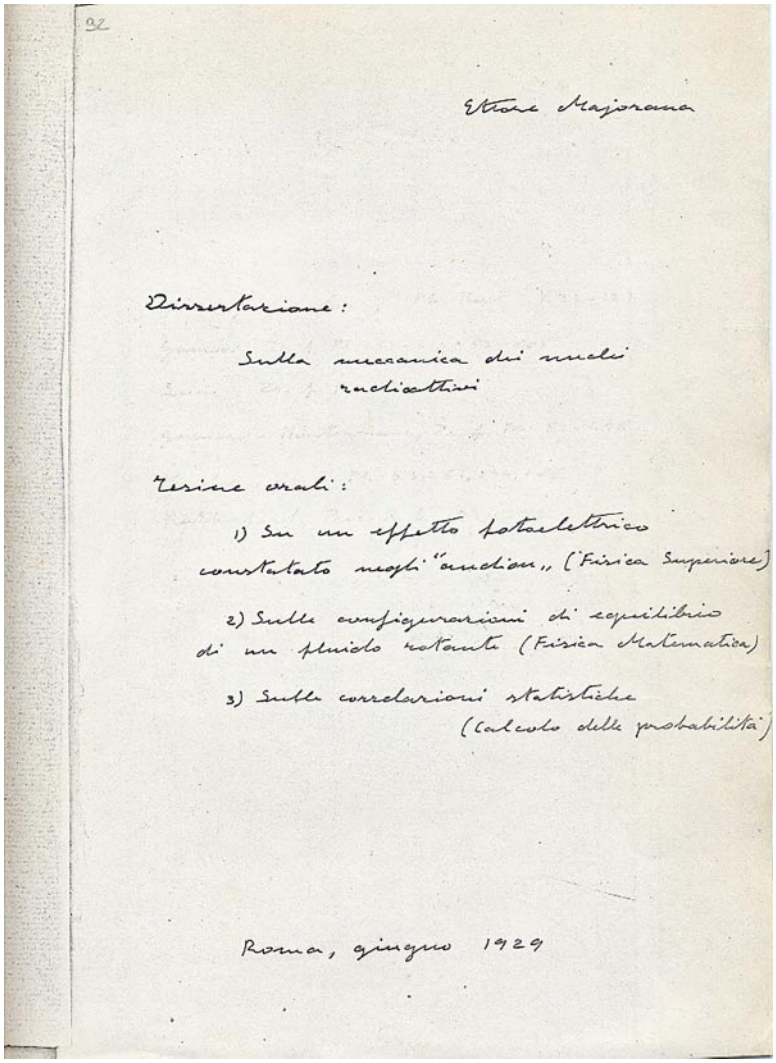

Fig. 2. – Majorana thesis: first page (Domus Galilaeana, Pisa).

After Chapt. IV, we find the introduction and then the bibliography, both of which are identical to those we later find in the thesis, except that there they are moved to the beginning and end, respectively.

Note that between the various "chapters" there are some blank pages, typical of a work in progress because if necessary they allow for expansions of the various parts, without having to rewrite the whole. Some sentences are not present in the manuscript, but were added later by hand in the typescript. Chapter IV is reproduced in the thesis identically as it is in the manuscript.

Note the "particular" language which he uses to address the Commissioners, who will have to judge him. Majorana writes: " ...we will do this also so that the reader becomes familiar with the subject and where in the following the exposition will, of

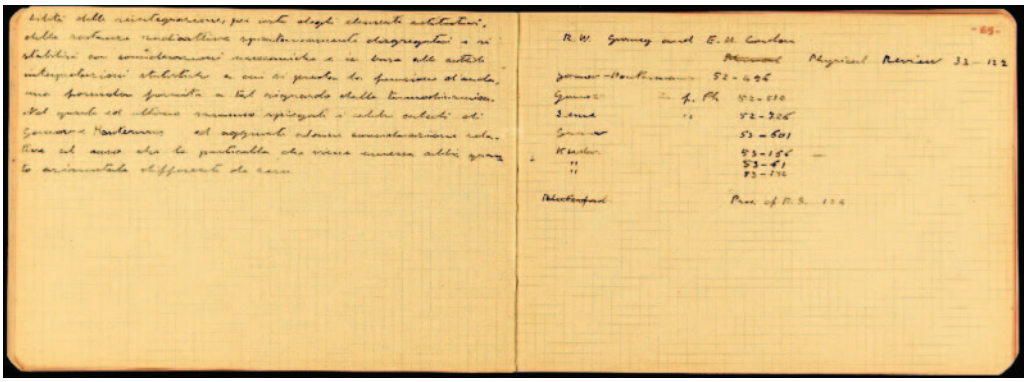

Fig. 3. – Notebook No. 10, last page and references (Domus Galilaeana, Pisa).

necessity, be unclear, is ready to fill the gaps and to provide, to a large extent, his precious collaboration".

A manuscript text with the identical title, "Crash of an α-particle against a radioactive nucleus", can be found, in addition to the thesis and in notebook No. 10, also in a previous notebook of Majorana, classified as "volume II", and which, we can say, represents the beginning of Majorana's interest in Nuclear Physics topics. Here we find in a very sketchy form what will later be developed by Majorana in his thesis (fig. 4).

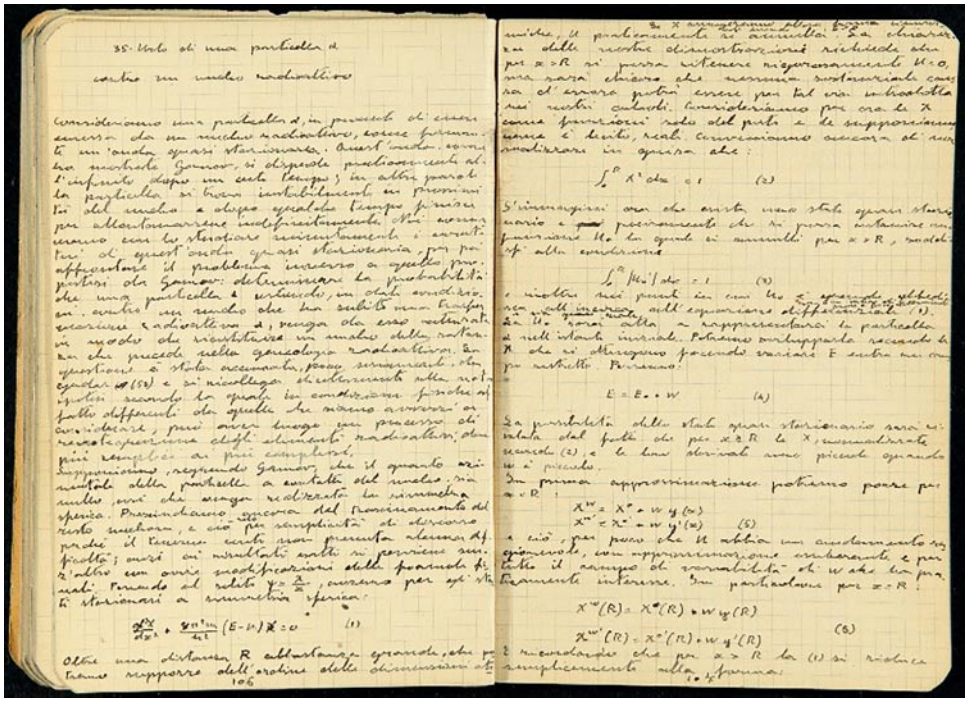

Fig. 4. – Volume No. 2, pp. 52–53 (Domus Galilaeana, Pisa).

In this short text an article that Kudar published on 1 February 1929 is cited with the abbreviation (Kudar 53), and therefore we can say that it dates back to after this date of 1929, (December 1928) and not, contrary to what is claimed by Bonolis *et al.* in the spring of 1928. This postponement of the birth of Majorana's interest in Nuclear Physics reinforces our idea that Majorana began looking for a new topic for his thesis, different from the statistical model of the atom, only after his Communication to S.I.F. in December 1928.

5. – The thesis

The thesis, although short, in its final draft appears as a text very dense with ideas and results. However, it is noticeable that it is written in a very hasty and incomplete way. There is no conclusion. As already mentioned, the first and last pages, respectively the title page and the bibliographical references, are handwritten; on the title page, a generic "June 1929" is used as the date; the bibliographical references are not classified as Bibliography, but are listed in alphabetical order of the authors, without a heading, without reporting the titles of the works cited and without being referred to in the body of the thesis, for example with a number. If Majorana wanted to graduate in early July 1929, as in fact happened, he had little time available. In about six months he had to take four exams, which were very demanding, write a thesis, on a topic other than the statistical model of the atom on which he had worked in the last year, and prepare three essays. So a certain haste is more than justified. However, Majorana, according to his usual style, intervenes authoritatively in the problem, fully entering the international debate on Gamow's theory, highlighting, on the one hand, its importance and, on the other hand, its limits.

In fact, he recognizes it as having allowed Nuclear Physics "to have made a first and important step", but at the same time he is aware that "the explanation of radioactive phenomena", which it proposes is "incomplete".

And it is precisely on this point that he immediately sets to work, trying to correct the mathematical defects and trying to give a rigorous theoretical treatment to the quantum phenomenon that is at the basis of the theory.

In particular, referring to the tunnel effect, as Gamow had already done, but using in a different and more appropriate physical context, *i.e.*, the Schrödinger equation for the alpha particle bound in the nucleus, that is, considering it centered at an initial instant in a region inside the nucleus, he demonstrates that in fact there is a non-zero probability that the particle can escape from the trap in which it is forced to stay and can find itself at great distances from the nucleus with a very high speed.

Majorana's concluding sentence is: "The preceding considerations show how his [Gamow's] procedure is justified".

In summary, the fundamental physical structure present in the thesis is a metastable quasi-stationary structure, constituted by the nucleus and the alpha particle, with an appropriate interaction that seems to confine the alpha particle in the nucleus, but in reality allows it to escape due to the peculiar quantum evolution, in which the tunnel effect intervenes.

In particular, starting with an initial wave function completely concentrated in the nucleus, it is shown that with a certain probability after a very long time the particle can be found very far from the nucleus, with a certain determined energy.

Conversely, by shooting an alpha-particle against the nucleus with a certain determined energy there is a non-zero probability that it will be captured in the nucleus. This

scheme of metastable structures will be widely present in Majorana's subsequent works at the atomic level. Indeed, it can be considered almost as the Leitmotif of his research.

Furthermore, Majorana takes into consideration the criticisms made by Kudar to Gamow, at the beginning of 1929, correcting some of his statements, and demonstrates that a term introduced by Gamow and criticized by Kudar "does not imply paradoxes, as Kudar seems to believe".

During the course of the thesis, he then reinforces "the applicability of Gamow's method" and finally clarifies some calculations developed by Gamow together with Houtermans and arrives at the conclusion that, using his method, it is possible to derive a formula that "does not differ, except for the form, from the expression used by Gamow and Hautermans".

So Majorana, in the space of a few months, still a student, manages to obtain substantial and well-documented results, not only on the statistical model of the atom, but also on alpha nuclear decay, improving the original settings of Fermi in the case of statistics and Gamow in the case of Nuclear Physics.

In the thesis, original and very interesting results are achieved, which however do not find an outlet in official publications. Also the topic treated will no longer be addressed in Rome.

Majorana himself will no longer officially deal with Nuclear Physics until 1933. A possible reason is that in that very year other authors were intervening on alpha decay, including Theodor Sexl with an article "Zur Quantentheorie des Atomkerns" (On the theory of the atomic nucleus), published in *Zeitschrift für Physik* [15], reaching the same results as Majorana and thus making his further intervention obsolete. In short, Majorana saw a work ready for publication burned, through no fault of his own. Taking into account Majorana's scientific activity, up to the communication to the Congress in December 1928, and the usual practice of degrees, according to which the thesis was followed by a Subcommittee, we now give credit to a rumor circulating within the family circles, which has come to our attention, according to which Majorana was forced to rewrite the thesis. It could be assumed that Majorana at the beginning of 1929 was preparing, or that he intended to prepare, a thesis on the improvement of the statistical model of the Fermi atom, according to the general strategic lines set out in the Communication.

This paper, or rather, this project, however, had not found the approval of the Subcommission, whose spokesperson was Enrico Fermi himself. So the Subcommission had proposed, with Majorana's assent, that an alternative text be presented, on a different topic.

Hence Majorana's thesis on alpha decay, later rightly defined as "the degree thesis of a brilliant mind", was born. Naturally at this point the rift between Majorana and Panisperna Institute was absolute and could no longer be healed.

6. – Conclusion

Therefore, from what we have seen, Majorana was forced to change the subject of his thesis, moving his research interests from a field he had already developed, such as the statistical model of the atom, whose developments however led him to an irreconcilable conflict with his thesis supervisor, Enrico Fermi, to the Nuclear Physics of alpha decay which was developing at an international level.

It is surprising that, despite his entry into the field at the last moment, Majorana still managed to give fundamental contributions, essentially supporting Gamow's theory,

which had also been heavily and apparently definitively criticized by other authors, such as von Laue and Kudar.

The fundamental fact is that Majorana works following his own methodological ideas that allow him to effectively jump from one topic to another and to effectively connect to the latest developments of the topics covered.

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