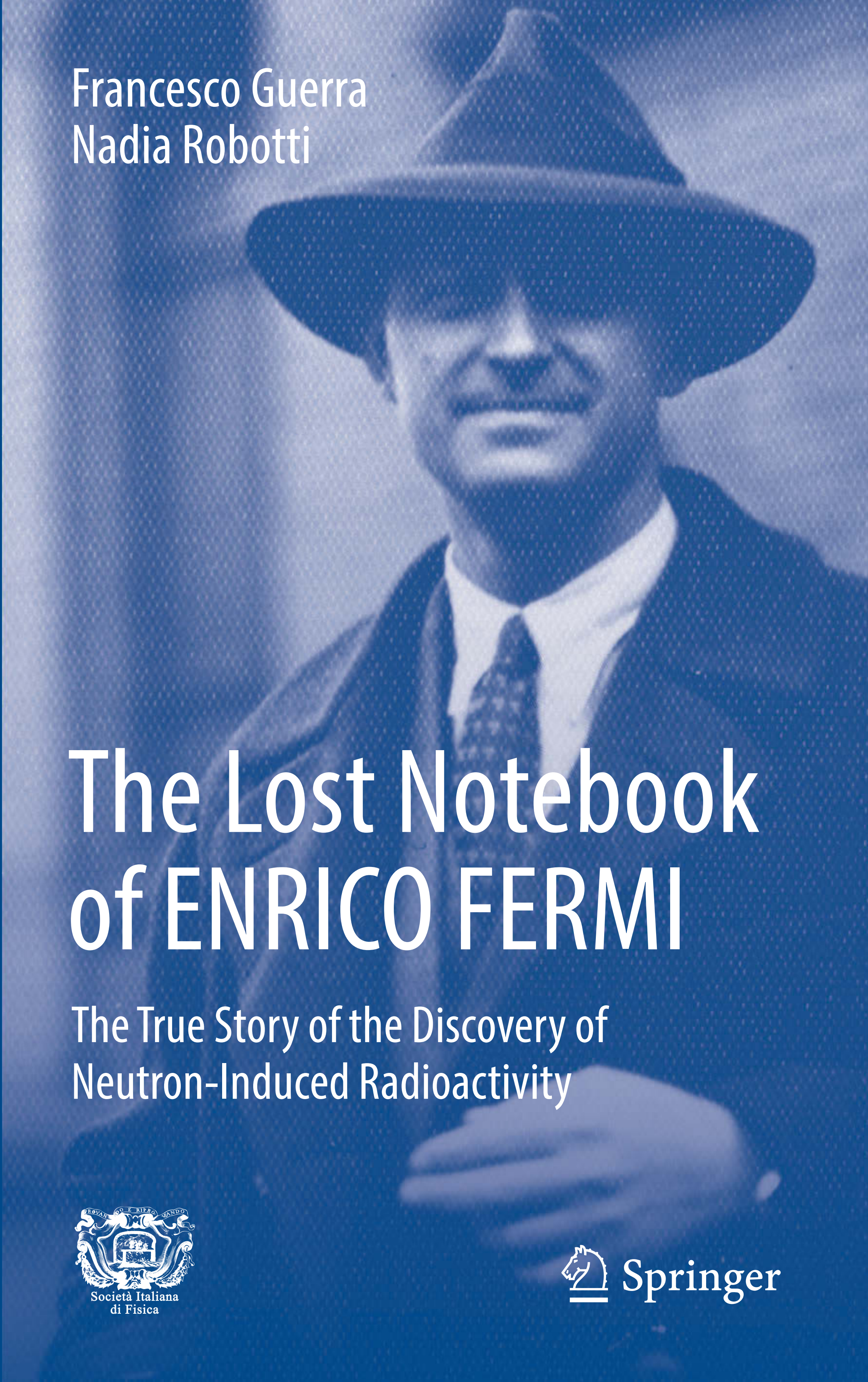

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The Lost Notebook of ENRICO FERMI

The True Story of the Discovery of Neutron-Induced Radioactivity

Società Italiana di Fisica

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Foreword and acknowledgements

Thanks to Enrico Fermi some extraordinary developments took place in the period December 1933 - October 1934 at the Regio Istituto Fisico (Royal Physics Institute) of the Royal University of Rome in via Panisperna. These developments in nuclear physics led first to the creation of an extremely advanced theoretical model to explain beta nuclear decay and then to the discovery of radioactivity induced by neutron bombardment, together with the extraordinary effects of slow neutrons on the activation of some important nuclear reactions. These developments soon made the Istituto Fisico in Rome the foremost centre for nuclear physics research at an international level. Full recognition of this came when Enrico Fermi was awarded the Nobel Prize for Physics in 1938.

It is fascinating to understand what the conditions were that made this kind of miracle possible and exactly how these important discoveries were made. In particular, by using Fermi's first laboratory notebook, which we have identified at the Fondazione Oscar D'Agostino in Avellino, it is possible to follow in real time the whole process that led to the discovery of neutron-induced radioactivity.

In this book we also study the beginning of nuclear physics research in Rome in the national and international contexts. We see that in national research planning for this sector, organised by the Consiglio Nazionale delle Ricerche (National Research Council) in 1933, Rome was initially assigned a rather marginal task, directed towards nuclear gamma spectroscopy, which fitted well with Rome's research tradition. But very soon, through an incredible sequence of events, Enrico Fermi completely disrupted this line of planning and let Rome acquire a key role of strategic relevance in neutron physics which would then become the basis for all future developments in this sector.

The success of the nuclear structure model developed by Ettore Majorana during his stay in Leipzig in 1933, which considerably improved the proton and neutron model previously introduced by Werner Heisenberg, also played an important role in Fermi's drastic change to the direction of lines of research in Rome.

In 1938 Fermi, after being awarded the Nobel Prize in the ceremony in Stockholm in December, carried out his decision to emigrate permanently to the United States. A few months earlier, at the end of March, Ettore Majorana suddenly disappeared in circumstances which are still not entirely clear. Within a few months Italy lost its two greatest experts in nuclear physics.

In the course of our research we have consulted archive material belonging to several institutions, including the "Archivio Centrale dello Stato" in Rome, the "Domus Galilaeana" in Pisa, the Special Collections Research Center of the University of Chicago, the "Institut Curie" in Paris, the "Accademia Nazionale dei Lincei" in Rome, the

"Accademia Nazionale delle Scienze detta dei XL" in Rome, the "Fondazione Oscar D'Agostino" in Avellino, the Department of Physics of the University of Rome "La Sapienza", the "Archivio Occhialini-Dilworth" at the University of Milan, the Churchill Archives Centre in Cambridge, the California Institute of Technology in Pasadena, the Duke University in Durham, the University of São Paulo in Brazil, the Nobel Foundation in Stockholm, the "Massimiliano Massimo" Institute in Rome, the University of Rome "La Sapienza", the University of Palermo. To the directors and staff of all these institutions we express our grateful thanks for their courteous welcome, collaboration and assistance.

Special thanks go to:

– Carla Onesti of the University of Rome "La Sapienza", Francesco Marchetti and Maura Beghé of the Domus Galilaeana, Angelo Poggio and Mario Pomodoro of the Library of the Department of Physics of the University of Genoa, Natalie Pigeard and Anaïs Massiot of the Musée Curie in Paris, for their enthusiasm and friendly help in tracing material,

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– Ettore Majorana, Jr. for fruitful exchanges of opinion on Ettore Majorana's scientific, cultural and human personality, and for his generous willingness to allow us access to important documents,

– the Presidents of the Fondazione Oscar D'Agostino, who have succeeded each other over time, Michele Cardellicchio, Paolino Marotta, Pietro Caterini, who allowed us to access the documents and to reproduce them,

– Luisa Cifarelli for her friendly and affectionate encouragement.

This work was made possible by support from MIUR (Ministry of Education, Universities and Research), from INFN (National Institute for Nuclear Physics), from the University of Rome "La Sapienza", from the University of Genoa, from the Società Italiana di Fisica (Italian Physical Society), from the Museo Storico della Fisica and Centro di Studi e Ricerche "Enrico Fermi" in Rome.

FRANCESCO GUERRA and NADIA ROBOTTI

Buonabitacolo - Genova - Roma
10 July, 2015

In the present English version we have included some additional material coming from the ongoing research.

It is a pleasure to thank Angela Oleandri and Christine V. Pennison for the marvellous job they have done, for the deep cultural sensibility, and for the infinite patience.

FG & NR
10 September, 2017

Contents

1 Introduction

As is well known, in Rome in March 1934 Enrico Fermi (Rome, 29 September 1901 - Chicago, 28 November 1954) discovered neutron-induced radioactivity. For this discovery, and for the connected discovery in October that same year of the effect of the slowing down of neutrons, Fermi was awarded the Nobel Prize for Physics in 1938. The motivation read as follows: "for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons".

The discovery of neutron induced radioactivity and the consequent study of neutron physics opened up new frontiers for humanity, not only in the field of pure scientific knowledge but also in the field of applications to exploit nuclear energy, with significant consequences, for good and evil.

Much has been written about this discovery (made public by Fermi on 25 March 1934) by his closest collaborators (Edoardo Amaldi (1908-1989), Oscar D'Agostino (1901-1975), Bruno Pontecorvo (1913-1993), Franco Rasetti (1901-2001), Emilio Segrè (1905-1989)), by professional historians, and also by his wife Laura Fermi (née Capon, 1907-1977). With the exception of the book by Laura Fermi *Atoms in the Family: My Life with Enrico Fermi* [69], which was written while Fermi was still alive, all the other reconstructions were presented after Fermi's untimely death in November 1954.

We can now explain the reason for this book of ours.

All the historical reconstructions produced so far, which often contradict each other, are based essentially on direct or indirect testimony, often gathered years later, with all the typical drawbacks of personal recollections, and with a natural tendency, consciously or unconsciously, to stress aspects linked to the person's own contribution, variously perceived, and to consider events in relation to the person's own role. In July 2002, as we shall describe in detail later, through a series of happy circumstances, we identified one of Enrico Fermi's noteooks in the Library of the Istituto Tecnico per Geometri(*) "Oscar D'Agostino" in Avellino. This notebook, which covers all the work leading to the discovery of neutron-induced radioactivity, we can define as the "Nobel Prize first notebook". Together with the notebook we also identified a bundle of 16 sheets of paper which date to about the same period [3,4].

The laboratory procedures relating to the discovery of neutron-induced radioactivity

(*) A technical high school [Translator's Note].

F. Guerra and N. Robotti, *The Lost Notebook of ENRICO FERMI*,
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Fig. 1. – The Royal Institute of Physics in via Panisperna - DFUR.

are very simple and direct, and completely documented in the notebook. In this book we will carry out a detailed analysis of the contents of the notebook, especially of the most significant passages, to arrive at a complete reconstruction of the discovery. This reconstruction allows us to understand in depth the conceptual and operational procedure followed by Fermi during this first experimental undertaking in advanced nuclear physics research. Moreover it also helps us to understand how a laboratory notebook was kept in those days, and what we can glean from it. The methodology followed by Fermi, in its efficient simplicity, allowed him to arrive at results that were outstanding at an international level, even though he had very limited means available to him, such as those that existed at the time in via Panisperna (Fig. 1)(*). From this point of view, Fermi's progress provides a universal lesson, and one which is completely relevant today. The achievement of momentous results with very limited means constitutes the triumph of intelligence and creativity. A lesson to be pondered.

Naturally, for a complete appreciation of Fermi's investigations and the scope of his discoveries it is first necessary to offer a comprehensive description of the state of nuclear physics in those years. So the first seven chapters are devoted to a reconstruction of the developments in nuclear physics from the 1920s, when the neutron had not yet been discovered, to the spring of 1934 when Fermi began his experimental adventure with the neutron. Particular attention has been paid to the situation in Italy, above all in Rome where Fermi worked until 1938 before moving to the United States of America after

(*) The acronyms in the figure captions are all specified in the list of credits on page 256.

receiving the Nobel Prize in Stockholm in December 1938. His was an entirely Italian Nobel Prize!

In tackling this part, and also while analysing Fermi's notebook, we have tried to provide all the essential information necessary so that the contents of our book can also be used for teaching purposes, both in specific university courses, for example in a course on the History of Physics or of History of Science, but also in introductory modules of a historical nature on Nuclear Physics for other courses. The simplicity and intuitive characteristics of Fermi's experimental process should allow our description to be used also in the final years of secondary school education.

For a reconstruction of the history of the Physics Institute in Rome before Enrico Fermi's arrival we refer the reader to the book by Giovanni Battimelli and Maria Grazia Ianniello [15].

2 Fermi in Italy: his manuscripts

2.1 The "Fermi Archive" at the Domus Galilaeana in Pisa

As is well known, from his time in high school (1918) to his departure for Stockholm and then for the United States of America (1938), Enrico Fermi carried out intense and productive scientific research in Italy. The results obtained by Fermi in this "Italian" period are sensational. In a special Section, at the end of the volume, we provide a list of all Fermi's publications(*) in his Italian period, including minor works such as reports to conferences and contributions to non-scientific journals, expanding the list given in "Note e Memorie" (Collected Papers) [6], correcting some mistakes in the titles, and following chronological order. In some cases these minor publications are very useful in order to understand why Fermi made his strategic physics choices and why he adopted particular formulations. Fermi's activity in disseminating scientific culture is really stunning, as is borne witness to by the numerous articles in the "Atti delle Riunioni della Società Italiana per il Progresso delle Scienze" (Proceedings of the meetings of the Italian Society for the Progress of Science), by lectures, and by contributions to journals aimed at the general public, such as Sapere [F145] and Gerarchia [F95].

Let us briefly run through some points in Fermi's scientific output in Italy.

Let us first recall his work in 1926 "Sulla quantizzazione del gas perfetto monoatomico" (On the Quantization of the Monoatomic Ideal Gas) [F42], regarding the foundations of the quantum statistics of an ideal monoatomic electron gas, and more generally of a gas composed of particles that obey Pauli's exclusion principle. Fermi's statistics are historically called Fermi-Dirac statistics, due to the publication of similar results by Paul Adrien Maurice Dirac (1902-1984) a few months later, the result of independent research [63].

In 1927 the formulation [F56] of the statistical model of the atom appeared, followed by further developments and applications. This provides a semiquantitative method of calculating various atomic properties in the field of quantum mechanics. This model, which is still of great use, including in the field of astrophysics, is called the "Thomas-Fermi" model. Indeed Llewellyn Hilleth Thomas (1903-1992) had published analogous results a few months earlier [161] as far as the formulation of the model was concerned but limited only to the fundamental level.

(*) In this volume we refer to Fermi's publications by their number in the list, preceded by F, *i.e.* [F1], [F2] etc., to distinguish them from the ordinary bibliography.

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Fermi also arrived at the formulation of a quantitative theory of the hyperfine structure of spectrum lines (1930) from which the magnetic moments of many nuclei could be deduced [F73].

Furthermore Fermi presented an extremely simple and efficient formulation of quantum electrodynamics [F85] which formed the basis of the cultural and scientific training of an entire generation of Physicists in this area.

At the end of 1933 a theory of nuclear beta decay was proposed [F115], based on the hypothesis of the existence of the neutrino and on the remarkable idea that electrons did not pre-exist in the nucleus but were created, together with neutrinos, at the moment of their emission. This would then reveal itself to be the basis of all weak interactions between elementary particles. In March 1934 came the discovery of neutron-induced radioactivity [F120, 121, 122] and later the discovery of the effect of slowing them down [F140], followed by an in depth analysis of the properties of diffusion, absorption and slowing of neutrons in various material substances. For the discovery of neutron-induced radioactivity and the effects of slowing, seen also as the crowning achievement of his previous scientific activity, Fermi was awarded the Nobel Prize for Physics in 1938.

We are lucky enough to have here in Italy, at the Domus Galilaeana in Pisa, almost all the original manuscript documents relating to this intense research activity [106].

Altogether there are 27 notebooks, 9 laboratory notebooks, about 600 cards recording data, 38 manuscripts and typescripts, 39 letters, as well as a miscellaneous collection of personal documents. Most of this material, as Edoardo Amaldi tells us, was left behind by Fermi at the Physics Institute of the University of Rome before he left Italy permanently on 6 December 1938. After Fermi's death in Chicago on 28 November 1954 Amaldi, the only one of Fermi's associates still in Rome, after consulting the President of the Accademia dei Lincei Francesco Giordani (1896-1961) and various Colleagues, including Enrico Persico (1900-1969), Franco Rasetti, Emilio Segrè, decided that this material, together with other material recovered later in the house of Fermi's sister, should be entrusted to the Domus Galilaeana in Pisa, designated in the early 1940s as the key Italian institution for the study of the History of Science. This material is still housed today at the Domus Galilaeana, in safe keeping in two sturdy safes on the first floor of the splendid *palazzo* at 26 via Santa Maria, and it constitutes the so-called "Fermi Archive".

Amaldi observed in 1959, at the end of the article in which he presented "The Fermi Manuscripts at the Domus Galilaeana" [8] to the scientific community: "I am glad that these manuscripts are now kept at the Domus Galilaeana for future generations, beside other documents of men who have also honoured mankind with their thoughts and experiments".

To complete the picture we also make a few brief references to Fermi's academic career during his Italian period. He graduated in Physics at the University of Pisa on 4 July 1922 and was awarded the Diploma of the Scuola Normale Superiore on the 7 July immediately following. In 1925 he obtained the *Libera Docenza*(*) in Mathematical Physics. He was one of the three winners in the competition for the chair in Mathematical Physics at the University of Cagliari which concluded on 21 January 1926. He came second behind Giovanni Giorgi (1871-1950) and ahead of Rocco Serini (1886-1864). There was a head to head contest for first place between Giorgi, who received three votes from the board members Giovanni Guglielmo (1853-1935), Carlo Somigliana (1860-1955) and Roberto Marcolongo (1862-1943), and Fermi who received only two votes from the board members Vito Volterra (1860-1940) and Tullio Levi-Civita (1863-1941). According to a belief widely held in the via Panisperna group "Fermi was rather disappointed and upset by the outcome of the competition which he thought was unfair", as claimed by Emilio Segrè in the introduction to "Note e Memorie" [6]. In fact the only advantage of coming first of the three would have been that of being appointed immediately as Professor at Cagliari, as happened to Giorgi. Instead Fermi actually renounced the privileges of his second place, very chivalrously, in order that Rocco Serini, who had come third, could be appointed at Pavia.

In any case Fermi was not left without a chair. Indeed Orso Mario Corbino (1876-1937), a powerful Senator and Director of the Physics Institute of the University of Rome, immediately managed to launch a competition for the post of Professor of Theoretical Physics at the University of Rome. It was the first competition in Italy for this discipline. The examining board, made up of Gian Antonio Maggi (1856-1937), Michele Cantone (1857-1932), Antonio Garbasso (1871-1933), Quirino Majorana (1871-1957) and Orso Mario Corbino, unanimously put Enrico Fermi in first place of the three, followed by Enrico Persico in second place, with a majority of three votes out of five, and Aldo Pontremoli (1896-1928) in third place with a unanimous vote. Fermi immediately took up his post as Professor in Rome on 1 January 1927.

By Royal Decree on 18 March 1929, proposed by the Head of Government Benito Mussolini (1883-1945), Fermi was nominated as a member of the newly created Accademia d'Italia. Great satisfaction for this event is expressed in a page of notebook No. 2 at the Domus Galilaeana where Fermi noted "A VII - 18 - 3 - 29 - Incipit vita nova – Gaudeamus igitur!" (A New Life begins - So let us Rejoice) (Fig. 2). It is one of the very few personal displays in a research notebook of Fermi's where he echoes the words of a well-known student song: "Gaudeamus igitur, Iuvenes dum sumus; ...". Finally Fermi received the 1938 Nobel Prize for Physics from the hands of King Gustav V in the ceremony in Stockholm on 10 December 1938.

On a more personal note, which is relevant for our understanding of later events, we recall that in a civil ceremony on 17 July 1928 Fermi married Laura Capon, a member of Rome's Jewish community, the daughter of Admiral Augusto Capon (1872-1943), an extraordinary character with firm personal convictions who was also a nationalist writer using the pseudonym Adriacus. His life was interwoven with the history of the Italian navy. Augusto Capon's life came to a tragic end following the roundup of Jews on 16

(*) Qualification entitling Fermi to teach at university level [Translator's Note].

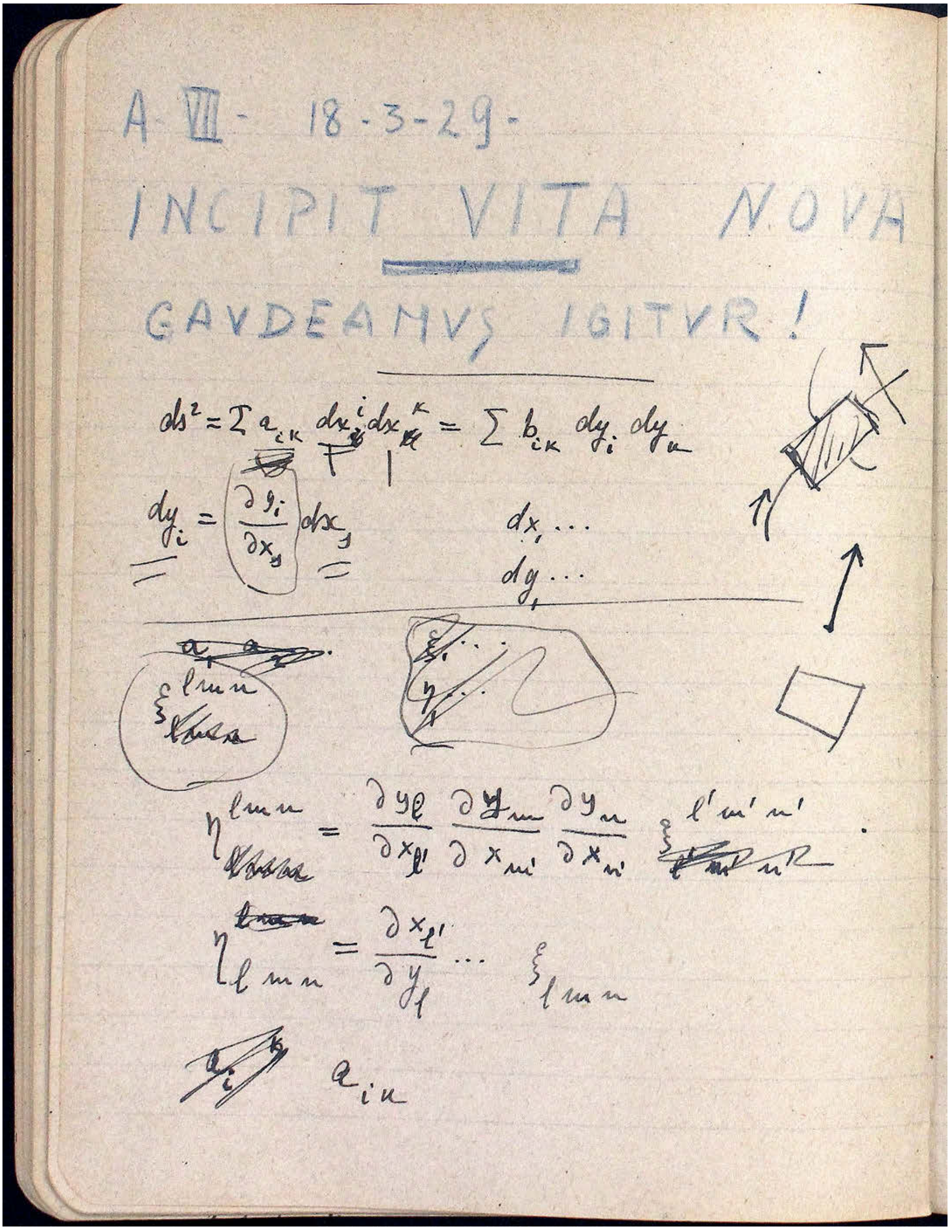

Fig. 2. – Fermi comments with satisfaction on his nomination as a member of the Accademia d'Italia (18 March 1929) - FDG.

October 1943 in Rome by the occupying German forces. Fermi's sister Maria told him about the dramatic day of Capon's arrest in a highly emotional letter, dated 4 July 1944 immediately after the liberation of Rome, which is preserved in the Fermi Archive at the University of Chicago.

Their children Nella (1931-1995), born on 31 January 1931, and Giulio (1936-1997), born on 16 February 1936, were baptized on 23 February 1936 in the church of Saint Bonosa in via Tirso according to a note in the Zanghi Archive at Sapienza University of Rome.

On the eve of their departure for Stockholm and the United States, on 5 December 1938, the Fermis also married according to Catholic rites, officiated by Monsignor Ernesto Ruffini (1888-1967), at the parish church of St. Roberto Bellarmino in Piazza Ungheria after Laura received the required baptism.

2.2 A gap in the Archive

A few years ago, when we began to study the birth and development of nuclear physics in Italy, consulting and reorganising the Fermi Archive in the Domus Galilaeana, we immediately noticed a strange gap.

The documents concerning neutron-induced radioactivity consist in all of nine laboratory notebooks and more than 600 cards of recorded data. They provide complete coverage of the experimental work carried out by Fermi and his team (Amaldi, D'Agostino, Pontecorvo, Rasetti, Segrè) in the period from 20 April 1934 until May 1935, when the research group was in practice disbanded, while Fermi's discovery of neutron-induced radioactivity was announced on 25 March 1934. So it seemed that more than a month of Fermi's research activity, in the decisive phase of the discovery, had left no written documentation. Recently however we found in Irpinia, at Avellino, two manuscript documents written by Fermi that cover exactly the period March-April 1934 and which allow us to fill in completely the gap we had met before.

It is a lined notebook of the same type as those entrusted to the Domus Galilaeana, characterized by the same brick red coloured cover and produced by the same Dutch company, together with a packet of 16 loose sheets.

The Irpinia notebook, we choose to call it that way to highlight its provenance, is lined, is made up of 78 pages and is written on both sides. The front of the notebook, which can be identified thanks to the paper mill's stamp at the bottom of the cover, is written by Fermi over 15 pages, numbered with circled numbers but without any dates, and is dedicated to problems relating to beta decay. The cover and some pages of the notebook and of the loose pages are shown in chapter 11, pp. 179-227. We indicate by Qf# the pages in the front of the notebook, by Q# the pages numbered from the back, and by S# (S#a) the front (back) pages of the loose sheets.

After the first fifteen pages, where these theoretical calculations are reported, the notebook was turned upside down so it could be used as a laboratory record for Fermi's subsequent experiments on neutron-induced radioactivity. This side of the notebook is composed of 141 pages, numbered by Fermi, with the first date, 27 March 1934, written at the top of page 44 (!), and the last, 24 April, written on page 140. This notebook contains both the preparatory procedures for the experiments and the entries of the measurements taken during the months of March and April 1934.

So the dates, but above all the contents, allow us to identify this notebook as Fermi's first notebook on neutron-induced radioactivity and therefore the notebook of the discovery.

The loose sheets however start with the date 7 April 1934 and end on 20 April 1934 and therefore they concern the research carried out immediately after the discovery. They are written on both sides and, as we have been able to establish, were ripped out of another laboratory notebook, also on neutron-induced radioactivity, stored at the Domus Galilaeana. This notebook is identical to the Irpinia notebook, produced by the same firm, and was mainly compiled by Segrè so that it is conventionally known as the "Segrè Notebook", indicating "20-4-34" as the first date written at the beginning of the notebook. The notebook clearly shows that the first part had been forcibly ripped out. Moreover on the first page is the deep impression of some numbers, heavily traced in pencil on the last page but one of the 16 Irpinia pages.

So Fermi, after using and filling up the first Dutch notebook, presumably bought during his visit to Leiden a few years before, moved on to recording data in the second notebook. Around 20 April he tore out the 16 pages, which are the consistent continuation of the first notebook, and he passed the second notebook to Segrè so that he could record the measurements that had been assigned to him. In an initial phase these concerned the evaluation of the absorption of radiation in matter and are not directly connected to neutron-induced radioactivity.

Moreover, at the end of the last page of the bundle of 16 pages, "end of measurements / Segrè Notebook" is written. The handwriting of this note is Fermi's. Very probably Fermi intended to indicate with these words that the first phase of the research had been concluded. The results were reported in the first three publications under his name alone: the two letters to "La Ricerca Scientifica" on 25 March [F120] and in early April [F121] and the letter to Nature on 10 April [F122]. A new phase was opening up which directly involved his collaborators.

The story of the Irpinia notebook and of these 16 pages is very remarkable, as is that of their discovery.

Ever since way back in 1978, the Library of the Istituto Tecnico per Geometri "Oscar D'Agostino" in Avellino, later merged into the "De Sanctis - D'Agostino" Istituto Superiore di Istruzione Secondaria, has housed all the archive material that had belonged to Oscar D'Agostino (1901-1975), a chemist born in Avellino who had cooperated with Fermi in his research into neutron-induced radioactivity in the period 1934-1935.

This material was donated by Mrs Sofia Melograni, D'Agostino's widow, when the school was named after her husband in October 1978. On this occasion the "Oscar D'Agostino Foundation" was also established with the task of preserving this material and of offering scholarships in Oscar D'Agostino's name to particularly deserving students at the school.

Over the following years the "Oscar D'Agostino Archive" has been the subject of exhibitions and of some publications, in which some parts of it have also been reproduced. A preliminary inventory was compiled by Giovanni Acocella, a scholar of the History of Physics from Avellino, connected with the "Federico II" University in Naples, and presented by him at the XXII National Conference on the History of Physics and Astronomy which was held in Genova-Chiavari on 6-8 June 2002 [2]. Following this presentation, in July the same year, since at that time we were investigating Fermi's discovery of neutron-induced radioactivity, we joined Giovanni Acocella at Avellino in order to study in depth the contents of the D'Agostino Archive, hoping to find information about the chemical aspects of the research carried out in Rome into neutron-induced radioactivity since D'Agostino was acknowledged as the "group's Chemist". It was then that, to our great surprise, we discovered Fermi's notebook and the bundle of 16 pages amongst D'Agostino's papers. These documents had been ascribed to D'Agostino and had been classified as "Notebook No. 3" and "Notebook No. 4", respectively. Moreover some pages of "Notebook No. 3" had already been published as "D'Agostino's Notebook", even if the handwriting and the contents are clearly not D'Agostino's but Fermi's.

It is difficult to establish why these two documents, which represent the initial missing gap in the Fermi Archive at the Domus Galilaeana, ended up in D'Agostino's personal archive. Perhaps a possible answer is suggested by the Irpinia notebook itself which shows us, on the basis of the handwriting, that Fermi's first collaborator after the discovery was actually D'Agostino. So one might think that D'Agostino's initial, and as we shall see later, constant presence, above all in the early stages of the research, is a reason why these documents are now in Avellino. It is possible that they were given to D'Agostino personally by Fermi, as a testament to the contribution made by this Chemist, who is often relegated to a subordinate and marginal position in historiographical reconstructions, but whom Fermi however always recalled in his writings and thanked meaningfully. Another possibility is that after Fermi's death the notebook and the 16 pages were handed to D'Agostino by Amaldi so that he could have a memento of the period of his collaboration with Fermi.

2.3 How to proceed

The Irpinia notebook is very important, apart from its historical significance, because it represents the only direct and structured testimony of Fermi's discovery of neutron-induced radioactivity and it allows us to reconstruct the initial phase completely on the basis of objective documentation.

With regard to this first phase, the only document available to us was Fermi's Letter dated 25 March 1934 to "La Ricerca Scientifica", which at that time was the Official Journal of the recently founded Consiglio Nazionale delle Ricerche-C.N.d.R. (National Research Council), in which he announced the discovery [F120]. However this Letter is very concise, as we shall see. It only contains the essential information about the results without reference to the procedures followed. The same concision is to be found both in the second Letter to "La Ricerca Scientifica" [F121], and in the Letter to "Nature" [F122], written by Fermi immediately after the discovery, and also in the first extensive article written on the subject by Fermi and sent to "Il Nuovo Cimento" in May 1934

[F131].

Instead the Irpinia notebook affords a detailed reconstruction of all the experimental steps taken by Fermi, of his working rhythm, of his choices in methodology as well as in strategy, in the culminating phase of the discovery.

Moreover, together with the 16 loose sheets and the last 22 pages of a notebook of Amaldi's which we will discuss in chapter 8, it allows us to reconstruct the birth around Fermi of his first working group and the way it operated in this initial moment.

Finally, by analysing the Irpinia notebook, in the light of another of Fermi's laboratory notebooks stored in the Domus Galilaeana which Fermi himself named "Thesaurus Elementorum Radioactivorum" (Fig. 3), it is possible to establish the exact day and hour when Fermi discovered neutron-induced radioactivity: it was Tuesday 20 March 1934, around two o'clock in the afternoon, after a feverish night spent fine tuning the counter and the amplifier and repeated background measurements.

In any case, before proceeding with an analysis of Fermi's discovery which is the main focus of our book, we thought it was appropriate, as we have already anticipated in the introduction, to set this discovery both in the framework of the Physics of the time, giving ample space to the development of Nuclear Physics, starting with the first International Conference on Nuclear Physics organised in Rome in 1931, to the discovery by Frédéric Joliot (1900-1958) and Irène Curie (1897-1956) of alpha particle-induced radiation announced on 15 January 1934 [59], and also in the more specific context of the research carried out in Rome with regard to the atomic nucleus, from the first beginnings with the *Laurea*(*) Thesis of Ettore Majorana (1906-1939) in July 1929, to the creation of a bismuth crystal spectrograph to study gamma radiation (November 1933) and the production of a source of radium D from which polonium could be periodically extracted (December 1933), which in practice were never fully used.

(*) The *Laurea* is the degree issued by the Italian Universities that includes a research thesis and leads to the title "Dottore". It is therefore of a higher level than a Bachelor degree in American or British Universities.

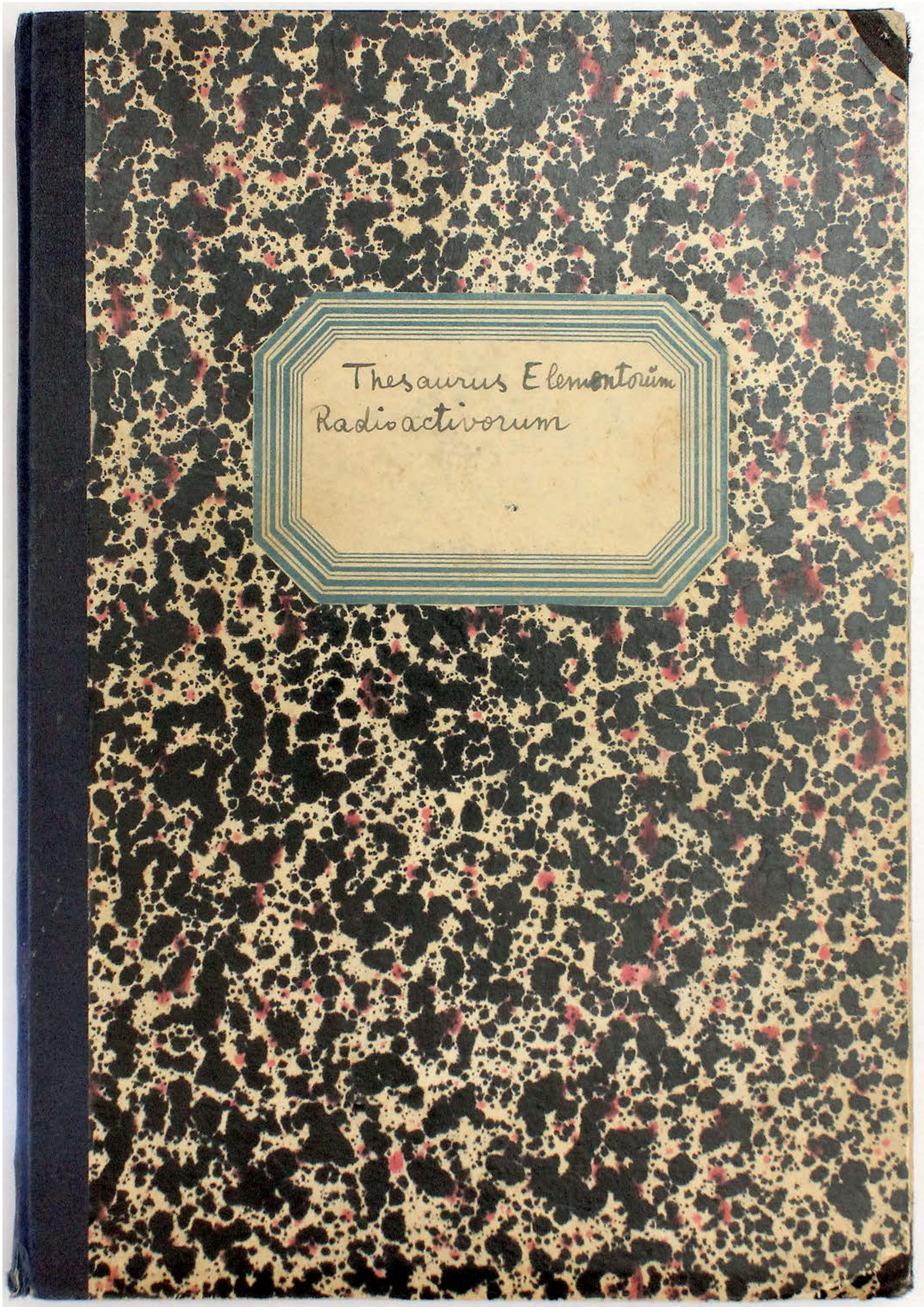

Fig. 3. – The laboratory notebook that Fermi named "Thesaurus Elementorum Radioactivorum" (1934) - FDG.

3 The beginning of Nuclear Physics in Rome

3.1 Fermi and Nuclear Physics: the first steps

From 1928, immediately after the formulation of the statistical model of the atom (later called the "Thomas-Fermi" model), until nearly the whole of 1932, Fermi was mainly interested in quantum electrodynamics, a cutting edge topic in those years, and studied in particular by Werner Heisenberg (1901-1976), Pascual Jordan (1902-1980), Wolfgang Pauli (1900-1958), P. A. M. Dirac. Between 1928 and 1932, Fermi published no less than seven papers on the subject, one of them in collaboration with Hans Albrecht Bethe (1906-2005) [F97].

The reason for Fermi's new interest is to complete atomic physics, which at this point was firmly based on the quantum mechanics of Heisenberg, Schrödinger (1887-1961) and Dirac, also with regard to the problems of radiation. In a talk given in Rome on 31 March 1931 at the XXIV Adunanza Generale della Società Italiana di Fisica (XXIV General Assembly of the Italian Physical Society), of which an abstract was published in "Il Nuovo Cimento" [F94], Fermi "expounds the problem of constructing quantum electrodynamics and illustrates its crucial conceptual interest bringing together in a single edifice the quantum theory of radiation on the one hand and the mechanical laws to which charges are subject and Maxwell's laws on the other".

In these papers Fermi succeeded in writing, both in the non-relativistic and the relativistic case, the equations of a system made up of an electromagnetic field and by any number of charges, introducing a new, in his view "simpler", formalism compared to that used by Heisenberg and by Pauli. The method followed by Fermi "consists basically of considering the coefficients of the expansion into harmonic components of the scalar and vector potentials at a given time as dynamic variables that characterise the electromagnetic field" [F85]. Fermi justified his own paper as follows: "Since the methods followed by these Authors are essentially different from mine, I believe that it would not be pointless to publish my results too".

This attitude was actually typical of Fermi, consisting of elaborating original and direct methods to treat problems at the frontiers of research, openly confronting the structures set by other authors. One of the recurring characteristics of Fermi's methods was their fruitful simplicity. This style would also be fully displayed in his later experimental activity.

In his second paper devoted to quantum electrodynamics Fermi wrote as follows: "The

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final form in which the results of this paper will be expressed is particularly simple. Indeed we will find that the Hamiltonian which, according to the correspondence principle, represents the natural quantum translation of classical electrodynamics is obtained by simply adding to the Hamiltonian of Dirac's theory of radiation a term which represents the electrostatic energy of the system of electric charges; so that, in the present form, quantum electrodynamics is not in any way more complicated than Dirac's theory".

These papers had, amongst other things, the undeniable importance of making accessible topics that were formally very complicated, so much so that one of the articles in Italian [F85] was chosen to be included in the volume edited by Julian Schwinger (1918-1994) [159] which contains a collection of classic articles on quantum electrodynamics. In any case Fermi, in approaching quantum electrodynamics, in operational terms seized on the methods, of second quantisation and quantum field theory, such as had been developed at the time. As we shall see in chapter 6, it would be these methods that, once applied to the problem of beta decay, would allow Fermi in 1933 to arrive at his famous theory and to head towards the discovery of neutron-induced radioactivity.

Fermi however, while he was concerned with quantum electrodynamics, also began to express interest in Nuclear Physics. The first time that his name appeared linked to Nuclear Physics themes was in 1929 when he acted as supervisor for Ettore Majorana's thesis for his laurea in Physics. Majorana's thesis indeed concerned alpha nuclear decay (see [83]).

In 1929, when Majorana was developing his thesis, Nuclear Physics was a completely new topic compared to the lines of research that had been followed in Rome until then. These in fact had mainly been themes of classical physics or of quantum mechanics applied to the atom, in relation to spectroscopy, statistics and, more recently, as we have just said, in relation to electromagnetic radiation. The only exception is a note by Giovanni Gentile Jr. (1906-1942) (at that time an assistant in Rome for a six month period) which appeared in the "Rendiconti dell'Accademia dei Lincei" in February 1928 [79], concerning a model of the nucleus, still based on classical mechanics, which Ernest Rutherford (1871-1937) had posited the year before to explain alpha decay [149], and to which Giovannino Gentile put forward a series of very profound criticisms.

Majorana's thesis, with the title "Sulla meccanica dei nuclei radioattivi" (On the mechanics of radioactive nuclei), presents the result of research into alpha decay of nuclei, presumably begun in 1929 judging by the bibliography indicated, which amongst others quotes a very recent article by George Gamow (1904-1968) and Friedrich G. Houtermans (1903-1966) "Zur Quantenmechanik des Radioaktiven Kerns" [74], accepted on 29/10/1928 and published in issues 7-8, closed on 17/12/1928, of "Zeitschrift für Physik". The thesis was presented on 6 July 1929 to obtain a *Laurea* in Physics. In the report of his scientific activity, presented by Majorana in 1932 attached to his application for the *Libera Docenza* in Theoretical Physics, the title of the thesis was changed significantly with the addition of the word "Quantum" to become "On the Quantum Mechanics of Radioactive Nuclei" (see [83]). There are two original typescript copies of the thesis, with formulas added by hand by Majorana: a bound copy kept in the Family archive, the other in loose pages in the "Giovanni Gentile Jr." archive in the Department of

Physics at Sapienza University of Rome which also contains a note written by Gentile.

The subject was at that time extremely topical. Indeed a few months earlier George Gamow (1904-1968) [73], and independently Ronald Wilfred Gurney (1898-1953) and Edward Uhler Condon (1902-1974) [87], had succeeded in giving an explanation for alpha decay compatible with the experimental data in the setting of quantum mechanics, on the basis of the recently discovered tunnel effect, thus showing for the first time that this new mechanics could also be applied to nuclear phenomena.

Majorana's Thesis is the first work on the application of quantum mechanics to Nuclear Physics carried out in Rome, and more generally in Italy. In it a rigorous mathematical justification is given of Gamow's treatment of alpha decay which had received some serious criticisms in the scientific press. The thesis had a certain success. For example it was asked for (through Giovannino Gentile) by the nuclear physicist János (Johann) Kudar in Berlin who was very interested in the subject. However, even if original and very interesting results were arrived at, fully competitive at an international level, they did not lead to any outlet in official publications. Even the subject dealt with by Majorana would not be tackled at Rome again. Until 1933 Majorana himself would not concern himself again, at least officially, with Nuclear Physics. Nevertheless his results in 1933, which we will discuss later, are connected conceptually to the problems dealt with in his thesis, in reference to the possibility of applying quantum mechanics to nuclear structure. In the case of alpha decay this happened because the alpha particle, which is a heavy particle, was considered phenomenologically as having its own individuality in the nucleus even before decay. As for nuclear structure generally, it would be necessary to wait for the definitive elimination of the supposed "nuclear" electrons from the nucleus. But this could only happen after the discovery of the neutron in 1932.

In Fig. 4 we see Ettore Majorana's *libretto*(*).

Anyway in the years immediately following Majorana's thesis Fermi began to devote himself in person to subjects connected in some way to Nuclear Physics, turning his attention to the study of the hyperfine structure of atomic spectra. This choice is clearly linked to his previous activity in atomic physics, and in particular to his experience acquired in spectroscopy. Hyperfine structure, as Fermi observed in [F83], could be counted among the "phenomena that describe, so to speak, properties outside the nuclei", because due to the interaction of the nuclear magnetic moment with the orbital magnetic field of the electrons. It did not therefore directly involve "events that occur inside the nucleus", and could certainly be described in the setting of quantum mechanics.

As well as the famous fine structure, shown by the splitting of the energy levels due to the spin of the electrons and the relativistic corrections of their motion, the spectral lines, above all those emitted by the heaviest atoms, if observed with a high-resolution spectrometer, also show in some cases a hyperfine structure. These spectral lines appear split into several very close components separated from each other. The effects of the

(*) The booklet issued by Italian universities to their students for identification purposes [Translator's Note].

Fig. 4. – Ettore Majorana in his university *libretto* - FDG.

hyperfine structure are about three orders of magnitude smaller than those of the fine structure.

Already in 1924 hyperfine structure, excluding that which varied with the variation of the isotopic composition of the elements, had been explained by Pauli in the setting of old quantum mechanics, assuming that the nucleus had an intrinsic angular momentum (spin) associated with a magnetic moment.

Because of the coupling of this nuclear magnetic moment to the magnetic field produced by the external electrons, each energy level splits into various sublevels, giving rise to the various components that constitute the hyperfine structure of a spectral line, as had been seen in the experimental context. On the basis of this explanation, it was possible in principle to deduce, by means of a comparison between the hyperfine structures of the experimental lines and of the theoretical ones, the value of the angular momentum and of the magnetic moment of the nucleus, and thus obtain precious information about its inner composition.

Rita Brunetti (1890-1942) for example, in a review article which appeared in "Il Nuovo Cimento" in 1930 [30] wrote about the possibilities and the advantages of hyperfine structure studies: "Faced with the nuclear problem the physicist of today was perplexed for a while; but he is now gladdened that he can lift, at least partially, the veil that surrounds the material part of the atom without new technical inventions, without resorting to dissolving forces which for now seem inaccessible".

Fermi worked on hyperfine structure from the end of 1929 and throughout 1930, publishing three papers, including a Letter to Nature [F72, F73, F74], and delivering a talk to the XIX meeting of the Società Italiana per il Progresso delle Scienze (SIPS) in 1930, with the title "Sul momento magnetico del nucleo" (On the magnetic moment of the atomic nucleus) [F86]. This was never published however.

In these papers Fermi developed a quantum theory of hyperfine structure which could be used to evaluate the magnetic moments of many atomic nuclei. Examples of the application of this theory were then given by Fermi himself for the nuclei of sodium, rubidium and caesium. Fermi would return to the subject of hyperfine structure in 1933, publishing in collaboration with Segrè, a definitive work "sulla teoria delle strutture iperfini" (On the theory of hyperfine structures), in which, amongst other things, certain anomalies, seen experimentally in some hyperfine structures, were interpreted as a perturbative effect. In the version written in Italian for the Memorie dell'Accademia d'Italia [F107] the authors thanked Majorana for his theoretical contribution. The acknowledgement was omitted in the contemporary slightly modified version written in German for the international journal "Zeitschrift für Physik" [F108].

In the end the study of the hyperfine structure proved not to be a very accurate method to obtain information about the nucleus. Indeed Fermi himself observed in 1932 [F100] that "calculations of this type can so far only give hints of the order of magnitude of the magnetic moment of the atomic nucleus". Even so the results obtained by Fermi in this sector were such as to earn him two important invitations: the first, to the Solvay Conference in 1930 devoted to "Le Magnétism", where Fermi presented a report "Sur les Moments Magnétiques des Noyaux" [F87], the second to the 186th regular Meeting of the American Physical Society, which took place in Chicago in June 1933 and was defined in the Proceedings of the Conference [36] as "Perhaps until then the most important scientific session in its history", where Fermi gave a public lecture on the "Theory of hyperfine structures" [F113].

In any case, apart from these results in the area of hyperfine structure, Fermi's name in the nuclear field would soon become famous for another reason: as the organiser of an International Conference in Rome which made a mark in the history of Nuclear Physics.

3.2 The first International Conference on Nuclear Physics: Rome, October 1931

From 11 to 18 October 1931 an International Conference on Nuclear Physics was organised in Rome at the Physics Institute of the Royal University. This was, without exception, the first International Conference in this field. The opening session was held instead in Villa Farnesina, headquarters of the Accademia d'Italia. The history of this Conference, reconstructed through the documents preserved in the archive of the Accademia d'Italia, now kept at the Accademia dei Lincei, is particularly significant.

The year before this Conference (1930), on the initiative of the Società Generale Italiana di Elettricità - Edison in Milan and with financing from the same company, the

"Fondazione Alessandro Volta" was established and affiliated to the Reale Accademia d'Italia. The "Academic" council of this Foundation was chaired by the Nobel prize winner for Physics and Senator of the Kingdom Guglielmo Marconi (1874-1937). As a representative of the Società Edison, Orso Mario Corbino, then Director of the Physics Institute of the University of Rome and also a Senator of the Kingdom, was a member of the council. The Foundation's "most important aim" was to "convene annual meetings of scientists and scholars to discuss a topic that every two years must reflect subjects that fall within the competence of the Class of Physical Sciences and, in the intervening years, subjects within the domain of the other classes: Moral and Historical Sciences, Literature, Art". the privileged position reserved for the Class of Physical Sciences compared to the other classes must be stressed.

For the organisation of the first Conference — the inaugural Conference to be held in 1931 — Enrico Fermi, then Professor of Theoretical Physics at the University of Rome and a member of the Accademia d'Italia, was chosen as General Secretary with Guglielmo Marconi as Honorary President, Orso Mario Corbino as Effective President, and Bruno Rossi (1905-1993) (Florence), Antonio Carrelli (1900-1980) (Catania) and Gleb Wataghin (1899-1986) (Turin) as Secretaries.

For this Conference — as can be seen in particular in the letters sent by Fermi to the various participants and their replies (Figs. 5-12) — the theme initially chosen was "Nuclei and Electrons".

Even though we read the word "Electrons" in the title, and even if we find famous names in this field amongst the various invited scientists, such as John S. E. Townsend (1868-1957), John A. Fleming (1849-1945), Robert A. Millikan (1868-1953), Arthur H. Compton (1892-1962), and also Joseph J. Thomson (1856-1940) and Paul A. M. Dirac (who however were unable to participate), the central point of the Conference in the intentions of the organisers was reserved for the nucleus. Indeed the Proceedings of the Meeting [1], published in 1932, appeared with the title "Convegno di Fisica Nucleare" (Nuclear Physics Conference) (Fig. 13), and the reference made to "Electrons" throughout the Conference mainly concerns the electrons which, at that time as will be amply explained later, were believed to exist inside the nucleus.

According to the organisers in that precise moment in history the importance of delving into the study of nuclear phenomena is essentially linked to two questions. On the one hand, the instruments with which this field could be addressed from the theoretical point of view seemed to be available, at least in part. This was thanks to the complete development of non relativistic quantum mechanics and to the beginning of the relativistic extension of the wave equation and of the debate on the interaction between radiation and particles (that is to say with the beginning of quantum electrodynamics), A recent example of this was the success achieved by G. Gamow in 1928 [73], and independently by R. W. Gurney and E. U. Condon [87], in developing a theory for alpha nuclear decay based on the tunnel effect in quantum mechanics. On the other hand, after Rutherford arrived at the first nuclear disintegration in 1919, obtained by bombarding nitrogen with alpha particles, and with the consequent discovery of the proton [147], research into the artificial transmutations provoked by alpha particles had already been firmly launched.