Enrico Fermi

ENRICO FERMI

COLLECTED PAPERS

(NOTE E MEMORIE)

VOLUME I

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EDITORIAL BOARD

For this volume Edoardo Amaldi, Enrico Persico, Franco Rasetti and Emilio Segrè (Editor-in-Chief) have been responsible for the editorial work as indicated in the introductions to the individual papers.

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* *Fisica ad uso dei Licei*, vol. I, pp. 239 e vol. II, pp. 243, Zanichelli, Bologna, 1929.

* *Molecole e cristalli*, pp. 303 Zanichelli, Bologna, 1934. Translated as: *Moleküle und Kristalle*, Translation by M. Schön and K. Birus, pp. VII–234 Barth, Leipzig, 1938.

* *Thermodynamics*, pp. VII–160, Prentice-Hall, New York, 1937. Translated as: *Termodinamica*, Translation by A. Scotti, pp. 179 Boringhieri, Torino 1958.

* FERMI–PERSICO, *Fisica per le Scuole Medie Superiori*, pp. 314 Zanichelli, Bologna. 1938.

FOREWORD

On Enrico Fermi's death many of his friends and admirers wished to commemorate him in some permanent fashion. It was immediately apparent that the greatest and most durable monument to Fermi was his own work, a monument that will last as long as the pursuit of scientific knowledge. Hence this publication of his "Collected Papers" sponsored and financed by the Accademia Nazionale dei Lincei and the University of Chicago Press.

Fermi's life and work bear testimony to the international character of science in its noblest form. This is reflected in the number of journals of different nations and languages in which his writings appeared. Indeed, we can trace from the changes in his publication media some of his personal history and of the history of science from 1922 to 1954.

Since in these volumes we do not reprint every word that Fermi published, the manner of selection should be explained. Fermi occasionally wrote several versions of the same paper. We decided to publish only the most detailed one, regardless of language. Where he published different translations of the same paper, the choice was in the following order: English, Italian, German, French. Only for a few exceptionally important papers have we included an English translation not by Fermi himself. Any attempt at systematic translation by someone other than the author seemed inappropriate, especially in view of Fermi's well-known concern for the precise expression.

Original manuscripts and other important documents relative to Enrico Fermi are to be found at the "Domus Galilaeana" in Pisa and at the Library of the University of Chicago.

Volume I contains a complete list of all known writings by Fermi up to his departure from Italy in 1938, except his articles in the Enciclopedia Italiana. The papers marked with a star have not been reprinted, either because they are translations or abbreviations of papers which are reprinted, or because they are hastily composed accounts, often written by other persons, of Fermi's popular lectures. Fermi's books are not included in these "Collected Papers".

The Editorial Board was chosen by the sponsors from among Fermi's close friends and collaborators. The editors have checked the text, corrected some misprints or minor errors, and adapted the vector notation to American or German usage. They have also tried to provide each paper with a preface, a short historical introduction written by a person qualified to give an authoritative account of the origin of the paper. We hope that these introductions may be of interest to historians and students of the process of scientific invention. We sincerely thank everybody who collaborated in writing them.

The publishers of the journals in which these papers appeared have graciously given permission for their reproduction. We wish to thank them all, especially the Accademia Nazionale dei Lincei, Rome; the American Physical Society; the Consiglio Nazionale delle Ricerche, Rome; Nature, London; The Royal Society, London; the Società Italiana di Fisica; Zeitschrift für Physik.

The Editorial Board is sincerely grateful to Professor Giovanni Polvani, President of the Società Italiana di Fisica, for his warm support of this project.

Thanks are also due to the John Simon Guggenheim Memorial Foundation for a fellowship which allowed one of us (E. S.) to work on the compilation of this volume.

The Editorial Board

BIOGRAPHICAL INTRODUCTION

by EMILIO SEGRÈ.

Enrico Fermi was born September 29, 1901, in Rome at Via Gaeta N° 17, the third child of Alberto Fermi and Ida De Gattis. His family originally came from the North Italian town of Piacenza. He grew up in Rome, where he attended grammar school and later the Ginnasio Liceo Umberto I. He then studied at the University of Pisa as a Fellow of the Scuola Normale Superiore, and in 1922 he received his doctorate in physics. In 1923, with a Fellowship of the Italian government, he went to Göttingen to work under Max Born; and in 1924 he moved to Leyden to work under P. Ehrenfest. He returned to Rome the same year and in 1925 became "Libero Docente". He then held a lectureship at the University of Florence, and finally, in 1926, he was appointed Professor of Theoretical Physics at the University of Rome, where he remained until 1938.

In 1938 the Fascist racial laws, which affected his wife Laura Capon and her relatives and moreover deeply offended his sense of fairness, induced him to emigrate to the United States of America. Here, he was at first Professor of Physics at Columbia University in New York; then, during the Second World War he devoted all his activity to the development of nuclear energy on a large scale at Chicago, Illinois and at Los Alamos, New Mexico. At the end of the war, in 1946 he moved to the new Institute for Nuclear Studies at the University of Chicago, where he remained until his early and unexpected death on November 29, 1954.

These are the bare, external facts of Fermi's life. As is often the case with a man of science, they do not seem especially dramatic, although in his case the development of nuclear energy, more than emigration to America, certainly represented an event comparable in adventure to the discovery of a continent for an explorer.

The lamented circumstance of his early death has as a consequence that many of his contemporaries, collaborators and friends remember him well. In recounting their experiences with him they can try to reconstruct a living image of the man. This is highly desirable because many scientists have the natural desire to know personally, as it were, the major worthies of their craft. What physicist has not had the curiosity to learn what kind of a man Galileo, Newton or Maxwell was? How did he work? How did his ideas originate? These questions are not easily answered by the ordinary biographies, generally written by authors with little personal and scientific contact with their subject. In Fermi's case, however, the fact that he collaborated extensively with other scientists, who were often his own pupils, makes it easier to reconstruct his scientific portrait. For this reason, while the single papers here collected speak for themselves scientifically and give the finished product of his work, we have tried as often as possible to provide for each of them an introduction written by whoever is in a position to be well informed of the circumstances which led to that specific investigation. While these introductions can add but little to the scientific interest of the papers, we hope that they may contribute to a reconstruction of the picture of the scientist as we knew him.

If we examine Fermi's works as a whole, we find them still fresh and interesting, often written with rare pedagogical skill. In a certain sense, the papers make easy reading, so that an able student can profit greatly from their study, even as a beginner; at the same time, they often have such deep implications that they have inspired very difficult and recondite investigations. The typical style of Fermi's writings is a close reflection of his personal and intellectual history. We see it evolve as time goes on from the early papers written at Pisa, in almost complete isolation, on a variety of disconnected problems, to the late papers in Chicago when he was a mature physicist and a great leader in the field, investigating theoretically and experimentally, with numerous co-workers, a whole new chapter of physics.

In the following pages I shall try to render Fermi's image as it appears to me.

Fermi's interest in mathematics and physics manifested itself very early. He told me that when he was about ten years old he had seriously struggled to try to understand why a circle was represented by the equation $x^2 + y^2 = R^2$, and had finally succeeded only after great efforts. This episode gives us a measure of his development at that age.

A little later he must have made considerable progress because while still an adolescent he read, in Latin, a book entitled "Elementa Physicae Mathematicae" by "Andrea Caraffa e Societate Jesu, in Collegio Romano". This is an ample treatise of mathematical physics published by a Jesuit in 1840. Its two volumes comprise approximately 900 pages and they cover mechanics, optics and astronomy, using the resources of analysis. Fermi acquired the book in a used-book stall and must have studied it quite diligently because the book has numerous marginal notes and developments of the calculations in his handwriting.

We know that what little outside help Fermi received came mostly from Ingegnere A. Amidei who was among the first to notice the boy's extraordinary ability. In this connection we have the invaluable first-hand testimonial of Ing. Amidei as set forth in a letter by him to E. Segrè. He states that sentences quoted verbatim were noted by him in writing at the time of his conversations with Fermi. We quote here Ing. Amidei's letter:

"Antignano (Livorno).

"November 25th, 1958.

"Having had the opportunity of guiding and counseling Enrico Fermi in his studies during his youth from his 13th to the end of his 17th year, I deem it appropriate to hereby summarize his course of study during the above-mentioned period, which was from the autumn of 1914 to the autumn of 1918.

"In 1914 I was Principal Inspector of the Ministry of Railways, and my colleague was Chief Inspector Alberto Fermi. When we left the office we walked together part of the way home, almost always accompanied by the lad Enrico Fermi (my colleague's son), who was in the habit of meeting his father in front of the office. The lad, having learned that I was an avid student of mathematics and physics, took the opportunity of questioning me. He was 13 and I was 37.

"I remember very clearly that the first question he asked me was: 'Is it true that there is a branch of geometry in which important geometric properties are found without making use of the notion of measure?' I replied that this was very true, and that such geometry was known as 'Projective Geometry'. Then Enrico added, 'But how can such properties be used in practice, for example by surveyors or engineers?' I found this question thoroughly justified, and after having tried to explain some properties that had very useful applications, I told him that the next day I would bring him – as I did – a book on projective geometry by Professor Theodor Reye [1] that included an introduction which, in a masterful, artistic style succeeds, by itself, in explaining the usefulness of the results of this science.

"After a few days Enrico told me that besides the introduction he had already read the first three lessons and that as soon as he finished the book he would return it to me. After about two months he brought it back, and to my inquiry whether he had encountered any difficulties, replied 'none', and added that he had also demonstrated all the theorems and quickly solved all the problems at the end of the book (there are more than two hundred).

"I was very surprised and since I remembered that I had found certain problems quite difficult and given up trying to solve them since they would have taken too much time, I wanted to verify that Enrico had also solved those. He gave me the evidence.

"Thus it was certainly true that the boy, during the little free time that was left to him after he had fulfilled the requirements of his high school studies, had learned projective geometry perfectly and had quickly solved many advanced problems without encountering any difficulties.

"I became convinced that Enrico was truly a prodigy, at least with respect to geometry. I expressed this opinion to Enrico's father and his reply was, yes, at school his son was a good student, but none of his professors had realized that the boy was a prodigy.

"I then learned that Enrico studied mathematics and physics in second-hand books that he bought at Campo dei Fiori, hoping to find one treatise that would scientifically explain the motion of tops and gyroscopes, but he could never find an explanation, and so, mulling the problem over and over again in his mind, he succeeded in reaching an explanation of the various characteristics of the mysterious movements by himself. Then I suggested to him that to obtain a rigorous explanation, it was necessary to master a science known as 'Theoretical mechanics'; but in order to learn

(1) T. Reye, *Geometria di Posizione*. Tr. A. Faifofer, Venezia 1884.

it he would have to study trigonometry, algebra, analytical geometry and calculus, and I advised him not to try the problems of tops and gyroscopes, since he would be able to solve them easily once he had mastered the field that I had outlined. Enrico was convinced of the soundness of my advice and I supplied him with the books that I thought were most suitable for giving him clear ideas and a solid mathematical base.

" The books which I loaned him and the date of the loan are as follows:

" In 1914, for trigonometry, the treatise on plane and spherical trigonometry by Serret.

" In 1915, for algebra, the course on algebraic analysis by Ernesto Cesàro and, for analytic geometry, notes from lectures by L. Bianchi at the University of Pisa.

" In 1916, for calculus, the lectures by Ulisse Dini at the University of Pisa.

" In 1917, for theoretical mechanics, the 'Traité de mécanique' by S. D. Poisson.

" I also deemed it appropriate for him to study the 'Ausdehnungslehre' by H. Grassmann which has an introduction on the operations of deductive logic by Giuseppe Peano. These books were loaned to him in 1918.

" I thought it appropriate because it was my opinion that the Ausdehnungslehre (similar to vector analysis) is the most suitable tool for the study of different branches of geometry and theoretical mechanics. . . . .

" Enrico found vector analysis very interesting, useful and not difficult. From September, 1917, to July, 1918, he also studied certain aspects of engineering in books that I lent him.

" In July, 1918, Enrico received his diploma from the Liceo (skipping the third year) and thus the question arose whether he should enroll at the University in Rome. Enrico and I had some long discussions on this subject.

" First of all I asked him whether he preferred to dedicate himself to mathematics or to physics. I remember his reply and I transcribe it here literally: ' I studied mathematics with passion because I considered it necessary for the study of physics, *to which I want to dedicate myself exclusively* '. Then I asked him if his knowledge of physics was as vast and profound as his knowledege of mathematics and he replied: ' It is much wider and, I think, equally profound, because I've read all the best known books of physics ' (*). I had already ascertained that when he read a book, even once, he knew it perfectly and didn't forget it. For instance, I remember that when he returned the calculus book by Dini, I told him that he could keep it for another year or so in case he needed to refer to it again. I received this surprising reply: ' Thank you, but that won't be necessary because I'm certain to remember it. As a matter of fact, after a few years I'll see the concepts in

(*) Persico says that one of them was the French translation of the large Treatise by Chwolson. During the Summer of 1918, Fermi went almost every day to the library of the " Istituto Centrale di Metereologia e Geodinamica " in order to study this book. Permission had been granted by the Director Prof. F. Eredia who had been Fermi's physics teacher at the Liceo Umberto I.

it even more clearly, and if I need a formula, I'll know how to derive it easily enough'.

"In fact, Enrico, together with a marvelous aptitude for the sciences, possessed an exceptional memory.

"I then considered that the proper moment had arrived to present a project that I had already considered in his behalf for a year, that is from the time when I advised him – and he immediately followed my suggestion – to study the German language, since I foresaw that it would be very useful for reading scientific publications printed in German without having to wait until they were translated into French or Italian. My plan was this: Enrico ought to enroll not at the University of Rome, but at the one in Pisa. First, however, he would have to win a competition to be admitted to the Scuola Normale at Pisa and attend (besides the courses in the School) the University of Pisa.

"Enrico recognized at once the soundness of my plan and decided to follow it, even though he knew that his parents would be opposed to it. Then I immediately went to Pisa to obtain the necessary information and the program for the competition to the Scuola Normale Superiore and immediately returned to Rome to examine it minutely with Enrico. I ascertained that he knew the subjects in the group of mathematics and physics perfectly, and I expressed my conviction that he would not only win the competition, but would also be the first among the applicants – as in fact he was.

"Enrico's parents did not approve of my plan, for understandable and human reasons. They said: 'We lost Giulio (Enrico's older brother, who died after a short illness in 1915) and now we are to allow Enrico to leave us to study at Pisa for four years while there is an excellent university here in Rome. Is this right?'

"I used the necessary tact to persuade them, a little at a time, that their sacrifice would open a brilliant career for their son and they finally agreed that my program should be carried out. Thus, as Enrico's wife wrote in her book 'Atoms in the Family', 'at the end, the two allies – Fermi and Amidei – carried the day".

Thus far goes the Amidei letter.

Persico tells of experiments undertaken together with Fermi at about the same time as that covered by the Amidei letter [2]. They are noteworthy especially for the choice of problems, such as to determine with high precision the density of Rome's drinking water (Acqua Marcia). This is a rather different problem from the more common one of a boy wanting to build some sort of an electric motor or apparatus: today this would be most probably a radio; at the time we are considering, it would have been a wireless telegraph. This does not preclude the fact that, at the time, Fermi was an expert builder of electric motors, but obviously he was also interested in more sophisticated problems such as the investigation of the behaviour of gyroscopes.

(2) E. PERSICO, «Scientia», vol. 90, pag. 36 (1955).

The point reached by his scientific development at the age of 17, when he finished his secondary schools, is clearly demonstrated by the entrance examination for the "Scuola Normale Superiore" at Pisa. The theme was "Distinctive properties of sounds" and is dated November 14, 1918. Certainly the examiners expected an essay at a high school level as one reasonably would. Instead, after a few introductory sentences, we find in his examination sheet the partial differential equation of a vibrating reed and its solution with the help of a Fourier series. The examiner, Professor G. Pittarelli, a very kindhearted man and a good mathematician in his own right, must certainly have been stunned by the little essay. Fermi himself told me that Pittarelli, after having read the examination paper, called him to ascertain whether the candidate really understood what he had written. After questioning him, Pittarelli said that during his long teaching career he had never met anybody like Fermi and that certainly the boy had extraordinary talents. Fermi remembered these occurrences many years later with obvious pleasure and deep gratitude towards Pittarelli.

In his other studies it is clear that at the Ginnasio and Liceo he progressed brilliantly and without effort. He was the sort of model student who succeeds in everything. His professor of Italian was Giovanni Federzoni, and Fermi who had an exceptional memory, knew long excerpts from the "Divine Comedy" and other Italian poems by heart and for the rest of his life was able to quote them on appropriate occasions. "Orlando Furioso" by Ariosto apparently was one of his favorite readings even before he had to read it at school; already when he was about 12 years old he could recite entire cantos by heart. For him one reading was sufficient to commit a section to memory. He must have been bothered by Greek, which was compulsory in Italian schools. At Los Alamos I once complained that in a sort of nightmare I had dreamed of a Greek final examination at the Liceo: Fermi confessed that he had been subject to the same nightmare.

His literary tastes were very simple; his own writings, including popular lectures, are not noteworthy for elegant literary style, especially in his early years. He had little sensitivity to literary form; to him the content was the only thing that mattered. On the other hand he was extremely careful, almost pedantic, as far as scientific precision was concerned. This care for precision increased steadily with time and one notices a remarkable difference in style between the early papers and those of his more mature years.

With regard to his knowledge of languages, he learned German as a boy, as Ing. Amidei mentions. The complexities of German grammar fascinated him. I think in his youth he could sit down and write an article in German without any mistakes, and he spoke it fluently; he knew French as many Italians do, using it easily but not always correctly. More than any other language except Italian he used English. He learned everything that one can by application and study, but the muscles of his mouth never became accustomed to English sounds, and he always retained a strong Italian accent, which occasionally irritated him. In America, Fermi devoted more effort to his English pronunciation than most immigrants are wont to do, but the result always remained imperfect.

Foglio I

16 Novembre 1918
Enrico Fermi

G. Pittaluga

Fisica

Caratteri distintivi dei suoni e loro cause.

Il suono consiste, come è noto, in rapide vibrazioni delle particelle d'aria che vengono messe in movimento, sia dai corpi vibranti in esse immersi, sia da qualunque perturbazione che possa tra di esse avvenire. Per poter quindi studiare completamente i caratteri dei suoni occorre che fermiamo dapprima la nostra attenzione sulle seguenti questioni: Come vibrano i corpi? Come l'aria trasmette le loro vibrazioni?

Per rispondere alla prima questione mi limiterò a trattare un caso particolare; le vibrazioni trasversali di una verga elastica incastrata a una estremità e perfettamente libera all'altra. Supporremo inoltre la verga omogenea, rettilinea e le vibrazioni piccolissime e piane. Prenderemo la posizione di riposo della verga per asse delle x e il punto di incastro per centro delle coordinate. Se con y indichiamo lo spostamento del punto di ascissa x al tempo t, le vibrazioni essendo piccolissime, si ha l'equazione

$$\frac{\partial^2 y}{\partial t^2} + a^2 \frac{\partial^4 y}{\partial x^4} = 0 \qquad (1)$$

dove per brevità ho posto $a^2 = \frac{EI}{m}$, m essendo la massa per unità di lunghezza, E il modulo di elasticità della verga ed I il momento d'inerzia della sua sezione. Poniamo

$$y = u_1 \operatorname{sen} k_1 t + u_2 \operatorname{sen} k_2 t + \ldots = \sum u \operatorname{sen} kt$$

dove $u_1, u_2 \ldots$ sono funzioni della sola x e le k sono costanti per ora indeterminate: si ha

$$\frac{\partial^2 y}{\partial t^2} = -\sum k^2 u \operatorname{sen} kt \qquad \frac{\partial^4 y}{\partial x^4} = \sum \frac{d^4 u}{d x^4} \operatorname{sen} kt$$

Sostituendo in (1) si vede che perchè essa sia verificata occorre che le u soddisfino l'equazione:

First page of Fermi's entrance examination for the admission to the "Scuola Normale Superiore" at Pisa.

$$a^2 \frac{d^4u}{dx^4} = K^2 u$$

Il cui integrale è

$$u = c_1 e^{\sqrt{\frac{K}{a}}\,x} + c_2 e^{-\sqrt{\frac{K}{a}}\,x} + c_3 \operatorname{sen}\sqrt{\frac{K}{a}}\,x + c_4 \cos\sqrt{\frac{K}{a}}\,x$$

c_1, c_2, c_3, c_4 costanti arbitrarie

Osserviamo ora che essendo la verga incastrata nel punto $x=0$ per $x=0$ si deve avere (qualunque sia t) $y=0$ $\frac{\partial y}{\partial x}=0$ e perciò anche $u=0$ $\frac{du}{dx}=0$

In più all'estremità libera, che corrisponde ad $x=l$ si ha

$\frac{\partial^2 y}{\partial x^2} = \frac{\partial^3 y}{\partial x^3} = 0$ e perciò $\frac{d^2u}{dx^2} = \frac{d^3u}{dx^3} = 0$. Vale a dire

$$\begin{aligned}
(u)_{x=0} &= c_1 + c_2 + c_4 = 0\\
\left(\frac{du}{dx}\right)_{x=0} &= c_1 - c_2 + c_3 = 0\\
& c_1 e^{\omega} + c_2 e^{-\omega} - c_3 \operatorname{sen}\omega - c_4 \cos\omega = 0\\
& c_1 e^{\omega} - c_2 e^{-\omega} - c_3 \cos\omega + c_4 \operatorname{sen}\omega = 0
\end{aligned}$$

Dove si è posto per brevità $\omega = l\sqrt{\frac{K}{a}}$

Ora perchè le costanti c possano avere valori non tutti nulli bisogna che

$$\begin{vmatrix} 1 & 1 & 0 & 1\\ 1 & -1 & 1 & 0\\ e^{\omega} & e^{-\omega} & -\operatorname{sen}\omega & -\cos\omega\\ e^{\omega} & -e^{-\omega} & -\cos\omega & +\operatorname{sen}\omega \end{vmatrix} = 0$$

Vale a dire ω deve soddisfare l'equazione

$$\cos\omega\left(e^{\omega}+e^{-\omega}\right)+2=0 \qquad (2)$$

Trascurando le radici negative, che non danno un risultato distinto perchè uguali in valore assoluto alle positive, è facile riconoscere che la (2) ammette infinite radici che differiscono assai poco da $\frac{\pi}{2}$, $\frac{3\pi}{2}$, $\frac{5\pi}{2}$ ....

Chiamandole ω_1, ω_2 ... si vede che K è uguale ad $\frac{\omega^2 a}{l^2}$

Se poniamo $K=\frac{2\pi}{T}$ (T è il periodo della vibrazione $\operatorname{sen} Kt$) si ha:

$$T = \frac{2\pi l^2}{\omega^2 a} = \frac{2\pi l^2}{\omega^2}\sqrt{\frac{m}{EI}} \qquad (3)$$

Ora dando ad ω i valori $\omega_1, \omega_2, \ldots$ si trovano i periodi T_1, T_2...
e si vede che la vibrazione complessa della nostra verga è decomposta

Second page of Fermi's entrance examination for the admission to the "Scuola Normale Superiore" at Pisa.

Fermi registered at the University of Pisa as a Fellow of the Scuola Normale Superiore in the fall of 1918. This school was founded by Napoleon in 1813 as a branch of the École Normale Supérieure of Paris. Its original purpose was the preparation of high-school teachers and the promotion of higher studies and research. Its pupils attend the University of Pisa, but in addition have special courses, mostly of the character of seminars. The pupils and professors live in the school as in a British college. Admission is by competition only and there are no fees of any kind. Several of the most distinguished literary and scientific figures of modern Italy studied there, and the roster of its alumni adds to the great prestige of the institution.

Fermi chose mathematics as his major subject but soon changed to physics. He conducted his studies at Pisa very independently. His grasp of physics was far above the local level of teaching and from his correspondence with Persico [3] we have some detailed information on how he spent his time. In February of 1919, as a freshman, he writes: "Since I have almost nothing to do for my class work and I have many books available, I try to enlarge my knowledge of mathematical physics and I shall try to do the same for pure mathematics". In the same correspondence he says that he has read Poincaré's "Théorie des tourbillons" and Appell's "Mécanique rationnelle" devoting himself especially to the methods of analytical mechanics. He also started studying Nernst's "Theoretische Chemie" and the "Lehrbuch der Allgemeinen Chemie" by Ostwald, chemical studies which he concluded "with some relief" a year later. We do not know where he learned the theory of relativity, although there is evidence that approximately at that time he had mastered Richardson's "Electron Theory of Matter", which expounds in fair detail whatever was known in 1916 concerning electromagnetic theory and atomic structure. A little later, probably in 1921, he read Weyl's "Raum, Zeit, Materie" and was impressed by the power and flexibility of variational methods which were used systematically in that book. He immediately assimilated the technique and the spirit of the method and proceeded to use it for new problems. Thus originated in his third University year his first published papers (N° 1, 2).

Among Fermi's papers at the University of Chicago is a very interesting document referring to his early university years. It is a small leather-bound note book which he filled between July and September, 1919, and which contains a sort of physics vademecum. It is divided in parts and, as was his habit, is written in pencil almost without erasure.

This booklet gives us a clear picture of Fermi's scientific preparation and intellectual progress in 1919 when he was between 18 and 19 years old. The first 28 pages contain a summary of analytical dynamics and are dated Caorso, July 12, 1919. In it he develops the theory of Hamilton and Jacobi, reaching very advanced topics with extreme concision, but equal clarity. There are no indications of his sources of information, but

(3) E. PERSICO, *loc. cit.*

very likely they are the works of Poincaré which he was studying around that time and also Appel.

Twenty-five pages on the electronic theory of matter follow; they are dated Rome, July 29, 1919, and they contain a résumé – as usual a very concise one – of the subject. In these pages he treats Lorentz's theory, special relativity, black-body theory, diamagnetism and paramagnetism. For this part there is also a bibliography listing several of the most important books on this subject, including Richardson's "Electron Theory of Matter" which we know he studied carefully.

Bohr's first papers on the hydrogen atom are also mentioned, although at that time they were little known and appreciated in Italy. The following section of 19 pages is dated Rome, August 10, 1919, and contains in greater detail the black-body theory according to Planck. This part is followed by an extensive bibliography on radioactive substances and their decay taken from Rutherford's " Radioactive Substances and Their Radiations ". There are no comments, and it is dated Caorso, September, 1919. The following chapter, from pages 81 to 90, is devoted to Boltzmann's H-theorem and kinetic theory and is dated Caorso, September 14, 1919. We find the usual succinct but clear exposition of theory with some applications. The method used for establishing the H-theorem is the same as that used by Boltzmann which involves a detailed analysis of all collisions. The booklet, totaling 102 pages, concludes with two bibliographies taken from Townsend's book on gas discharges. They deal with electrical properties of gases and photoelectricity. The last notes are dated Rome, September 29, 1919, and are followed by a table of contents.

This booklet shows many of the author's characteristics in an embryonic stage. The choice of material is made with surprising discrimination, especially if one considers the author's age and the fact that he was essentially self-taught. Another characteristic is that Fermi, although never repulsed or frightened by any mathematical difficulty, does not seek elegant mathematics for its own sake. Whether a theory is easy or difficult does not seem to concern him; the important point is whether or not it illuminates the essential physical content of the situation. If the theory is easy, so much the better, but if difficult mathematics is necessary, he is quickly resigned to it. One also notices an appreciable difference between the sections in which the logical structure of the subject predominates over its experimental content and those of a more empirical character. In the first, one perceives the master's hand; in the second, the lack of experience and of a critical evaluation of the many papers quoted is apparent. All told, it is surprising that after one year of university work a student should be able to put together such a booklet, which would be very creditable even for a teacher with a long educational career behind him.

The physicists with whom Fermi came in contact at Pisa are: Professor L. Puccianti, then Professor of physics and Director of the physics laboratory, Dr. G. Polvani, Puccianti's first assistant and two other assistants: Drs. Pierucci and Ciccone. Puccianti was gifted with a keen mind but was a lazy person who, while still young, had done some interesting work in atomic spectroscopy. At the time Fermi went to Pisa, Puccianti had ceased doing original research, although he remained interested in a deep and critical understanding of classical physics. Fermi became a good friend of Polvani. Among Fermi's classmates we remember Rasetti, who was very close to Fermi, and Carrara, who also had a fellowship at the Scuola Normale Superiore.

Besides studying physics Fermi also acquired a vast and deep knowledge of mathematics. As a matter of fact, even though he occasionally showed scorn for certain parts of mathematics which he deemed too formal or too little imaginative or too critical, he certainly was not mathematically naive or ignorant of the most modern and subtle mathematical questions. If needed, Fermi could give the most rigorous proof of a theorem, and often, on an example, he would show a refined critical approach, abandoning it later for the sake of speed and simplicity. There is no doubt that from his studies at Pisa he derived a supply of mathematical facts, ideas and methods that he used for the rest of his life. Whenever he needed an ingenious and powerful mathematical method, Fermi always had it ready in some corner of his mind, even when it involved mathematical notions above and beyond the common knowledge of professional theoretical physicists.

The studies at the Scuola Normale Superiore proceeded brilliantly: he always obtained the highest possible grades, except in drawing and in some chemistry courses. This cost him no effort and left him, as we noted, ample leisure for his private studies.

He enjoyed enormous prestige among his fellow students and his superior ability was recognized by everybody; indeed, it was known that the Scuola Normale Superiore had an extraordinary man among its students.

The doctoral dissertation, by tradition, was on an experimental subject, and its content is essentially reproduced in papers N° 6 and 7. The day of the oral examination the classroom was full, and his colleagues expected a memorable performance. Instead, the examination, although excellent, was not exceptional. Anyway, he obtained his degree *cum laude* in July, 1922. Three days later Fermi passed also the examination required for the "Diploma" of the Scuola Normale with a thesis on probability (N° 38). On that occasion some of the mathematicians made numerous remarks and criticisms of his solution of a certain equation; however, again he obtained the maximum of grades, *cum laude*.

Immediately hereafter, Fermi returned to live with his parents in Rome and at that time became acquainted with Senator O. M. Corbino, Professor of experimental physics and Director of the Physics Institute at the University of Rome. Corbino, although already at that time considerably absorbed in politics and business, was the most open-minded among all Italian physicists in a position of authority. Gifted with a brilliant mind, a true love for science and a generous human approach, he exerted an influence on the development of physics in Italy far greater than that derived directly from his scientific contributions. As long as he lived, he remained the wise advisor, friend and protector of Fermi and of the whole group which gravitated around him. The generosity with which he gave this necessary help, and the obvious satisfaction and delight with which he followed first Fermi's successes and then those of the group which populated Rome's Institute, are the clear signs of his superior intellect and generous heart. To my knowledge there are no documents or direct evidence of the relations between Fermi and Corbino around 1922. The acquaintance, which had quickly grown into friendship, between Fermi and the three distinguished mathematicians Castelnuovo, Enriques and Levi-Civita dates back to the same time. These three scientists were all at that time on the Faculty of Sciences at the University of Rome and taught there. Although they were professional mathematicians, they followed with more interest than most Italian physicists the developments of theoretical physics, especially in the field of relativity. Fermi also met Professor Volterra, who was primarily interested in problems of classical mathematical physics, but did not become especially intimate with him. These cordial relations with the mathematicians are reflected in the lectures that Fermi held at the Mathematical Seminar of the University of Rome, several of which appeared in print in the "Periodico di Matematiche", directed by Enriques (N° 22, 29, 34, etc). At that time there was no physics seminar at Rome and research was much more active in pure mathematics than in physics.

During the winter of 1923, Fermi won a scholarship from the Ministero dell'Istruzione Pubblica to study abroad and chose to work with Max Born in Göttingen. The time was a critical period of incubation for the new quantum mechanics, and Göttingen was one of the major centers involved; in spite of this, Fermi did not profit very much from his stay there. It is not easy to understand why this happened: we may surmise that his love for concrete, well defined problems, and his distrust of questions that he considered too general and abstract, may have repelled him from the then current speculations. These were certainly somewhat nebulous, and even worse for him, commingled with philosophical overtones; nevertheless, later they were destined to bring about the new quantum mechanics. The preference shown by Fermi for concrete problems especially in his early years, is probably to be traced to his cultural formation, and to the fact that he was practically completely self-taught. Concrete problems probably gave him the immediate sensation of the importance and a check of the correctness of his work, whereas general and abstract questions were much more difficult to plumb, and moreover isolation was a great obstacle in assessing the value of the results obtained. In later years Fermi considerably changed his objects of research and was less inclined to confine himself to detailed ingenious investigations of concrete problems.

From a personal point of view, it is barely possible that during the Göttingen period the physicists in his age group, such as Heisenberg, Pauli, Jordan and others, all men of exceptional talents, who should have been his companions, may not have recognized his ability and quite unintentionally left him out of their intellectual community.

Anyway, Fermi remembered the following months, when he moved to Leyden with a Rockefeller Fellowship to work in P. Ehrenfest's Institute, as more fruitful. Ehrenfest was one of the greatest teachers of physics and a man of warm human interests. Very early he recognized Fermi's ability and encouraged the timid young Italian. Anyone who met Fermi in later years might be surprised perhaps that he ever needed encouragement, but Fermi himself often mentioned the fact. While he was aware of his superiority over the physicists he had met in Italy, he said he did not have any way to compare his capabilities with those of the great international names. Ehrenfest, who personally knew most of the international figures, gave him just such a standard of comparison. The interests prevailing among Dutch physicists at the time are reflected in some of Fermi's papers (N° 21). And on the other hand some eyewitnesses, such as Uhlenbeck, relate that Ehrenfest, who had delved deeply in statistical mechanics, was impressed by Fermi's ideas on the ergodic theorem (N° 11).

On the whole, the time spent abroad does not seem to have been of decisive importance for Fermi's development, as it might have been had the circumstances in Göttingen proved more favorable. Fermi was accustomed to intellectual isolation and to learning from books and journals more than from personal discussions (a habit which he reversed in later years). He returned to Italy without having absorbed either the " spirit of Copenhagen " or that of Göttingen. Heisenberg's great papers on matrix mechanics of 1925 did not appear sufficiently clear to Fermi, who reached a full understanding of quantum mechanics only later through Schrödinger's wave mechanics. I want to emphasize that this attitude of Fermi was certainly not due to the mathematical difficulty and novelty of matrix algebra; for him, such difficulties were minor obstacles; it was rather the physical ideas underlying these papers which were alien to him.

When he returned to Italy in 1924, he began teaching an introductory mathematical course for chemists at the University of Rome. In 1925 he obtained the "Libera Docenza" and moved to the University of Florence to teach mechanics and mathematical physics. The physics laboratory, directed by Prof. Garbasso, was located on the Arcetri hills near the villa where Galileo spent his last years. In Florence he found Rasetti, who was at the time Garbasso's assistant. In February, 1926, Fermi took part in the competition for a chair of Mathematical Physics at the University of Cagliari in Sardinia. The referees were Professors Levi-Civita, Volterra, Somigliana, Marcolongo and Guglielmo. Whereas the first two favored Fermi, the majority chose for the first place Professor G. Giorgi, and Fermi remained with his temporary appointment in Florence.

Fermi was disappointed by the result of the competition, which he considered unjust; moreover, he naturally wanted to improve his modest financial conditions and was impatient to see his ability recognized officially.

Fermi's early correspondence with some of his closest friends, such as Persico, shows evidence that he was worried about his career. I mention this fact because later Fermi seemed to consider such preoccupations on the part of young scientists as something unnatural or exaggerated or strange. Probably once he had overcome the difficulties connected with the beginning of his own career, he took a more detached and lofty attitude towards these human vicissitudes, but at an earlier time he had certainly been anxious.

The Florentine period saw Fermi's first major contribution to theoretical physics: the discovery of the statistical laws which govern particles subject to Pauli's exclusion principle, or fermions as they are called today (N° 30). Soon after the discovery of this statistics, Corbino succeeded in having a chair in theoretical physics, the first in Italy, established in Rome and the competition for it was judged in November, 1926, by Professors Maggi, Cantone, Garbasso, Majorana and Corbino. They unanimously agreed that Fermi was the outstanding candidate, saying that " they felt they could rest on him the best hopes for the affirmation and future development of theoretical physics in Italy ". The other two successful candidates were his childhood friend, Prof. Persico, and Prof. Pontremoli. Fermi's actual appointment to Rome was opposed by an older member of the physics faculty, but Corbino readily overcame the obstacle. Persico replaced Fermi at Florence and in the fall of 1926 Fermi moved to Rome. In the Institute at Via Panisperna 89ª he started one of the most fruitful periods of his scientific career. The decade from the discovery of his statistics to 1936 was probably the golden age of Fermi's life.

The old physics building in Via Panisperna, although built around 1880, was still perfectly adequate for scientific work at that time and compared favorably with other major European laboratories. The equipment was fair and mainly included instruments for optical spectroscopy with good modern Hilger spectographs and adequate subsidiary apparatus. The shop was old-fashioned with rather poor machines; the library, on the other hand, was excellent. The location of the Institute, surrounded as it was by a small park on a hill in a rather central part of Rome, was convenient and beautiful at the same time. The gardens landscaped with several palms and bamboo thickets, the silence prevailing, except at dusk when many sparrows populated the greenery, made it a most peaceful and attractive center of study. I believe that everybody who worked there until 1937, when the physics department moved to the new "Città Universitaria", has still in his heart an affectionate and poetic feeling for the old place. The upper floor of the building was occupied by Corbino's residence; the first floor contained the research laboratories and the offices of Corbino, Lo Surdo and Fermi, as well as the library; the ground floor contained the shop, the classrooms and some laboratories for the students; the basement contained the electric generators and other facilities. Fermi, with Rasetti, and later with their students occupied the whole south side of the first floor; Lo Surdo most of its north side. As time went on, however, the number of people associated with Fermi increased so much that they filled most of the first floor. Neighboring quarters were occupied by Prof. G. C. Trabacchi, who was the chief physicist at the Health Department (Sanità Pubblica). He had an excellent supply of instruments and materials which he generously loaned whenever we needed them. This earned him the nickname of "Divine Providence".

Corbino, who used to spend part of the morning in his study, often visited Fermi's quarters and stopped to talk about physics and other subjects with him and his students.

When Fermi arrived in Rome he must have felt a strong urge to find an adequate scientific environment. There was then in Rome, as mentioned above, a group of eminent mathematicians considerably older than Fermi, such as Volterra, Levi-Civita, Castelnuovo, Enriques and others. Fermi was especially friendly with the last three, but the excellent personal relations and the high opinion which they had of each other were not sufficient to create intellectual exchanges; these were hindered by the essentially different points of view, scientific interests, and the considerable age difference. Among the physicists, Corbino was the only one open-minded enough and with sufficient preparation to follow and appreciate the developments of modern physics, the rapid progress of theoretical physics in general, and especially of quantum theory. However, he was busy with his political and business activities and, while he was fully aware of the necessity of rejuvenating physics in Italy and of introducing new young workers to the field, his direct scientific activity was limited. On the other hand, his political and administrative help and the enthusiasm with which he fostered the development of a physics school in Rome were of paramount importance.

The first step following the arrival of Fermi in Rome was Rasetti's transfer from Florence to Rome. He became Corbino's first assistant (Aiuto) and immediately started to try to revive experimental work. At this point I might introduce some personal recollections in order to illustrate the formation of the physics school in Rome. In 1927 I met Rasetti through a friend and a schoolmate of mine, G. Enriques, the son of the mathematician. While we went mountain climbing together, I learned from Rasetti several physical theories; but even more important, I gained a clear impression that physics in Rome was awakening. As a matter of fact, in 1925 I had already heard some lectures by Fermi at the Mathematics Seminar of the University. They had made a deep impression on me because they showed me for the first time a young man who was deeply versed in subjects of which I had barely caught a glimpse (by reading the quantum theory book by Reiche) but had never met in my regular university studies. However I had not yet met Fermi personally and I did not have any way of comparing the young lecturer with the famous men I knew only through my readings.

During the summer of 1927, through Rasetti and G. Enriques, I came to know Fermi personally and I immediately had the sensation of having found an exceptional teacher. Fermi himself, in conversations, on hikes and at the seashore, asked me several simple questions in mathematics and classical physics, perhaps to discreetly test my knowledge and ability. In September, 1927, on my return from an expedition to the Alps where I had been with Rasetti, G. Enriques and others, I went to the International Physics Conference in Como and there had the unforgettable experience of seeing in person the great physicists whose names I had read in books: Lorentz, Rutherford, Planck, Bohr and many others, and then a group of extremely young men: Heisenberg, Pauli and Fermi. It was clear that, scientifically at least, Italy was represented by Fermi. During the short period of the Conference I also learned a considerable amount of physics because Rasetti and Fermi would point out to me the various celebrities and at the same time tell me their most important achievements. I returned to Rome in the fall of 1927, decided to follow my old desire of studying physics, and within a few months left the engineering studies which I had been pursuing until then.

On that occasion for the first time I saw Corbino's far-reaching influence. He overcame with ease the far from trivial administrative difficulties in order to save me the loss of credit for one year of engineering studies. Without anybody taking special notice of it, I had become Fermi's first pupil, at least in a formal sense. The school in Rome had been started.

In June, 1927, without my having heard anything about it, Corbino had made an appeal to one of the undergraduate physics classes for engineers to enlist some new physics students: Edoardo Amaldi, the son of the mathematician Prof. Ugo Amaldi, followed this invitation, and thus he also entered the small group of students who were to be personally tutored by Fermi with the hope of developing among them research physicists and possible collaborators. Perhaps later this would lead, eventually, to a renaissance of physics in Italy. However this goal was not explicitly formulated at the time.

After a few months of study I talked to my friend and schoolmate at the engineering school, Ettore Majorana, and he also joined our group. Majorana, in intellectual power, depth and extent of knowledge, was much above his new companions and in some respects – for instance as a pure mathematician – superior even to Fermi. His exceedingly original intellect and, unfortunately, also his natural pessimism and exaggerated self criticism, drove him to work alone and to lead a solitary life. On the whole he did not participate very much in our work, and he limited himself to helping us in difficulties or to stunning us with his original and novel ideas and methods, or with his ability as a lightning mental calculator. Later he isolated himself even more, and by 1935 he had disappeared from the University, seldom leaving his private residence.

Other students frequented the Institute and once in a while attended Fermi's private lectures.

These were completely improvised and informal. In the late afternoon we met in his office and often conversational topics gave rise to a lecture: for instance, we would ask what was known about capillarity and Fermi would improvise a beautiful lecture on the mathematical physics of capillarity. In this fashion we reviewed many subjects at an intermediate level, more or less corresponding to a beginning graduate course in an American university or to the famous "Introduction to Theoretical Physics" by Planck or, in English, to the books by Slater and Frank. Sometimes, however, the level became higher and Fermi would explain to us a paper which he had just read: in this way we became conversant with the famous papers by Schrödinger on wave mechanics. We never had a regular "course". If there was an entire field of which we knew nothing and we asked Fermi, he would limit himself to mentioning a good book to read. Thus when I asked for some instruction in thermodynamics, he told me to read the book by Planck. However, the readings he suggested were not always the happiest ones because he probably mentioned only the books which he had studied himself, and these were not necessarily the best suited from a pedagogical angle. After his lecture, we would write down notes on it, solve (or try hard to) the problems which he had given us, or others which we ourselves invented. The rest of our time we spent on experimental work.

The instruction was chiefly in theoretical physics and no distinction was made between future theoreticians or experimentalists. Fermi himself, who at the time worked mainly in theory, was also interested in experimental work. His knowledge and interests embraced all physics, and he diligently read several journals. He preferred concrete problems and distrusted theories which were too abstract or general, but any specific problem, in any field of physics: classical mechanics, spectroscopy, thermodynamics, solid state theory and several more, fascinated him and was a challenge to his ingenuity and physical sense. Often just talking to him one saw a beautiful explanation develop, simple and clear, that resolved some puzzling phenomenon.

At that time we repeatedly had occasion to witness the execution of a new and original piece of work. Naturally it is impossible to say how much preliminary work Fermi had done consciously or unconsciously. Certainly there were no written notes. What one saw was the development of a calculation at a moderate speed, but with exceedingly few errors, false starts or changes of direction. The work proceeded almost as in a lecture, although more slowly, and at the end the manuscript, or at least the equations, were ready to be copied for publication with little need of improvements. A curious characteristic of Fermi's working habit was the steady pace at which he proceeded. If there were easy passages he still proceeded quite slowly, and a simple-minded observer might have asked why he wasted so much time on such simple algebra; however, when difficulties arose which would have stopped a man of lesser ability for who knows how long, Fermi solved them without a change of speed. One had the impression that Fermi was a steamroller that moved slowly but knew no obstacles. The final result was always clear and often one was tempted to ask why it had not been found long ago since everything was so simple and natural. Once used, a method was stored in his memory and often adapted to problems which appeared to be very different from the one which first originated the physical idea or mathematical technique. For instance, it is interesting to note the evolution and successive applications of the "scattering length" in papers N° 95 and 107, or the recurrence of the statistical theme applied to both atoms and nuclei.

Already at that time (1928) Fermi made little use of books: Laska's collection of mathematical formulae and Landolt–Börnstein's tables of physical constants were almost the only reference books he had in his office. If he needed some complicated equation to be found in a book in the library, Fermi would often propose a wager, saying that he would derive the equation faster than we could find it in a book. Usually he won. The only treatise that I know he read after he came to Rome was Weyl's " Gruppentheorie und Quantenmechanik ".

The speed at which it was possible to form a young physicist at that school was incredible. Naturally, a good deal of the success was due to the immense enthusiasm aroused in the young people, never by exhortations or sermons, but by the eloquence of Fermi's personal example. After some time spent at the Institute in Via Panisperna, one became completely absorbed in physics, and in saying " completely " I am not exaggerating.

Fermi did not like to assign subjects for doctoral dissertations, or in general to suggest subjects of investigation. He expected the students to find one by themselves or to obtain one from some colleague who was more advanced in his studies. The reason for this, as he later told me, was that he did not easily find subjects simple enough for beginners: he generally thought of problems that interested him personally and were too difficult for students. Rasetti was very generous in teaching the experimental techniques that he knew or in loaning apparatus that he no longer used, but it was difficult to work with him because he had peculiar idiosyncrasies and irregular schedules of work. A strong and long-lasting personal friendship developed among all the participants in this adventure. Age differences were small: Fermi, the oldest, was 26 years old in 1927; Amaldi, the youngest, was 19. Corbino occasionally came to the evening lectures, but the event was rare. However, he took a strong interest in the welfare of the group, in the career problems and relations of the young men with the rest of the world. As was to be expected, word of what was happening in Rome spread quickly among the young Italian physicists, and soon we started to receive visits from G. Gentile Jr., B. Rossi, G. Bernardini, G. Racah, G. C. Wick, and later we had for longer periods L. Pincherle, R. Einaudi, E. Fubini, U. Fano and many others. By 1929, it became clear that whereas the theoretical situation was well in hand, it was necessary to strengthen our experimental activities. To import new experimental techniques to Rome, members of the group had to work in different laboratories to learn them on the spot. Thus Rasetti went to Pasadena, to Millikan's laboratory where he did important work on the Raman effect; I went to Amsterdam to Zeeman's laboratory to study forbidden spectral lines and Amaldi went to Debye's laboratory in Leipzig where he worked on X-ray diffraction of liquids. Later we supplemented these visits, which at first had the purpose of using facilities not available in Rome, for the completion of problems already started there, by trying entirely new fields. In this connection, Rasetti spent some time at Dahlem in Lise Meitner's laboratory, and I worked in Otto Stern's laboratory in Hamburg. The plan was successful, and without these periods of experimental training it would have been impossible later to perform the complex neutron work rapidly and efficiently. However, even from abroad, we kept in close contact with the group in Rome, and either by letter or during vacations we discussed theoretical problems with each other. There are many traces of this exchange in papers by Fermi, Majorana, Wick and others. During this period Fermi went abroad only for short visits.

He was by now accustomed to being rather isolated intellectually because only Majorana (and he was rather inaccessible as mentioned above) could speak with him about theory on an equal footing. On the other hand, about that time, the first victims of Nazi persecution, barred from their native countries and attracted by Fermi, began to arrive in Rome. Bethe, Placzek, Bloch, Peierls, Nordheim, London and others spent some time in Rome, often on their way to the United States. Among the Americans, we had a visit by Feenberg, whom Majorana especially liked. This mutual attraction manifested itself by their sitting in the library facing each other in silence because they knew no common language.

Life in Via Panisperna was very methodical. One worked from about 9 a.m. to 12 : 30 p.m. and from 3 p.m. to 7 p.m. Of course this schedule was self imposed and everybody was free to keep it as he wished. Work in the evening was practically unknown and on Sundays we often went for a hike in the vicinity of Rome or for a mountain trip. During the winter there was always some skiing expedition, and during the summer, a trip abroad or a vacation in the Alps. Already in 1930 Fermi had gone as far as Ann Arbor (Michigan), attracted there by its brilliant summer school of theoretical physics and by his Dutch friends Uhlenbeck and Goudsmit who had moved there.

The most significant personal events of this period were Fermi's marriage to Laura Capon, in July 1928, and his appointment by Mussolini to the Italian Academy, in 1929. This honor, though well deserved, was unexpected because Fermi's reputation at the time was limited to physicists and, according to tradition, at his age, academic honors were not yet due. The appointment came probably at the instigation of Corbino, who, although not a Fascist, had been a member of one of the early cabinets of Mussolini. This event changed Fermi's financial condition and had a beneficial effect on the subsequent development of physics in Italy, since its representative in the National Academy was undoubtedly the most qualified man available. However, even after his appointment to the Academy, Fermi wielded relatively little political influence because he was unwilling to sacrifice any time to occupations outside of physics and he did not like to participate in administrative matters or political affairs. He was able to resign his post at the "Enciclopedia Italiana Treccani" (see e.g. N° 83) and at the National Research Council, which he had taken on his arrival in Rome, mainly because of his financial position. He made some desultory attempts at increasing research facilities by the creation of new jobs and subsidies, but these attempts did not go farther than obtaining Mussolini's approval on a memorandum which was later pigeonholed. It took many more years before the younger generation could prevail in the important matter of university appointments.

In the meantime, the most important scientific event of those years, the formation of quantum mechanics, had taken place without important contributions from Italy, at least in the establishment of the principles, but Fermi had contributed to its applications in an important way. Fermi's statistics was born independently of quantum mechanics and certainly before Fermi himself had mastered it completely. In the original papers we can trace this effort to clarify and assimilate quantum mechanics (N° 37, 39, 42) between 1926 and 1931. Schrödinger's papers were the first to be understood and aroused great interest and enthusiasm. Fermi explained them quickly to his friends; later to Corbino, who remained skeptical for some time; and still later he spoke on the subject to the Mathematics Seminar, where the professional mathematicians, older in age and less familiar with the experimental background of physics, raised several ingenious objections to the interpretation of quantum mechanics commonly accepted.

Thus, for instance, paper N° 59 originated from a discussion in which Prof. Castelnuovo raised many questions. Fermi was inclined to be somewhat impatient with people who did not understand the new developments of quantum mechanics, but naturally he treated very differently silly objections, of which there were many, and genuine difficulties, like those Castelnuovo raised.

Once in a while he complained that even persons for whom he had the highest respect and admiration, such as Corbino, would occasionally show a skepticism towards quantum mechanics and its interpretation which he deemed based on lack of understanding. It must be said, however, that in his last years Fermi seemed less convinced that the current interpretation of quantum mechanics is the last word on the subject. This resistance against quantum theory was shown mainly by people older than Fermi and his group, because the younger physicists either understood or believed the new theories, and in any case learned to use them, even if they had not completely assimilated them.

The advent of quantum mechanics in Fermi's opinion, and in Corbino's also, signaled the completion of atomic physics. The fundamental questions were solved, and the future lay in the direction of the exploration of the nucleus, or of complicated structures leading ultimately to biology.

This represented a radical change in the research projects of the Institute. We must remember that our experimental tradition in Rome went back to the spectroscopic work of Puccianti in Pisa: all our successes obtained up to that time in experimental physics were on spectroscopic subjects; the available equipment was spectroscopic; and our knowledge was mainly in the field of atomic physics. Rutherford and the work of his school were rather alien to us.

Thus the change to nuclear subjects cost us considerable effort. It was not a whim or a desire to follow a fashion, but was the result of a deliberate plan which we debated with plenty of vigor. The first step towards its realization was Rasetti's trip to Dahlem to learn nuclear techniques. A nuclear physics conference at Rome in 1931, organized by the Italian Academy, helped to familiarize us with current problems, and we changed the subject of our readings to matters connected with the nucleus. Fermi, later in his career, at the end of the Second World War, experienced a similar change in his field of work when he left neutron physics, in which he was recognized as the greatest authority, to study high energy physics.

The first work on a nuclear subject is the review article N° 72, and the first great success was the beta ray theory (N° 76), where we find the coalescence of previous work on radiation theory with Pauli's idea of the neutrino. A little later, artificial radioactivity research was in full swing. As the history of that period is told in detail in the introductions to papers N° 78, 84 to 110 and 112 to 119, it is omitted here. The neutron work absorbed Fermi completely for the remainder of the time he was to spend in Italy.

Unfortunately, the political horizon clouded with ominous signs. Since 1936, approximately, at the Institute we had a feeling of impending catastrophe. The days of serene, undisturbed work were gone forever. From 1930 to 1936, during a period of relative exterior quiet, we have the peak of Fermi's activity and the prime of the school in Rome. The history of this period is recounted in the introductions to the papers of those years. There is little to add. The neutron work was carried out with the kind of extreme rapidity that was possible only for a small group working in complete harmony and without administrative encumbrances. In this connection it is worth mentioning the low cost of this research. The Consiglio Nazionale delle Ricerche, on recommendation of its secretary, G. Magrini, immediately appropriated 20.000 lire (1000 U.S.A. dollars at that time) which could be spent with complete freedom. This was our only subsidy, apart from our regular salaries. The neutron work also had an untoward consequence: it became absolutely impossible for Fermi, because of lack of time, to continue his extracurricular teaching of promising young men; neither was he able to spare time for foreign visitors; from 1934 to 1938, first they became rare, then practically disappeared.

The Ethiopian war marked the beginning of the decline of the work at the Institute, and the death of Prof. Corbino on January 23, 1937, brought further serious complications. Prof. Lo Surdo was appointed director and he did not understand or appreciate the merit of Fermi's work. The Institute itself was moved to the new university campus, to a larger and more modern building; however, this move cost invaluable time. All these events and the grave political situation materially hampered Fermi's work. Finally, the Fascist racial laws of 1938 directly affected his wife and possibly his two children. This fact, and probably his deep, although mute resentment against an injustice that offended his sense of fairness, were the final arguments that convinced him to leave Italy. He was not to return to his native country again until 1949.

Already in the past Fermi had had offers of permanent positions from the Eidgenössische Technische Hochschule in Zürich and from several American universities. Some of these offers included not only substantial economic advantages, but also the availability of research facilities far superior to those in Italy. There is no doubt that Fermi considered these offers very carefully and several times was seriously tempted to accept them, but for various reasons he ultimately decided against them. The events of 1938, however, gave him a final impetus, and the award of the Nobel prize in Stockholm gave him a pretext to leave Italy while avoiding possible political reprisals. From Stockholm he travelled directly to New York, and thus began a second period of his life.

"Lo primo tuo rifugio e 'l primo ostello" (Thy first refuge and first home – Dante, Divina Commedia, Paradiso XVII, 70) was Columbia Univerin these Papers. Whoever has any scientific experience will be deeply impressed by a perusal of them. We find here a sequence of investigations connected with each other by an iron logic and a keen intuition; they stand equal to some of the major classical works of experimental science.

In the fall of 1942, during a visit to Chicago, Fermi locked me in a room with some of the reports (including numerical data and connected experimental results) on the exponential experiments and the theory of the pile.

I still remember how after a couple of hours of study I was dumbfounded by the success already reached and by the methods followed. Having read those reports, I saw clearly that a chain reaction with natural uranium was on the verge of being realized.

Indeed, on December 2, 1942, the pile under the Stadium of the University of Chicago became critical. This brought to an end another cycle of investigations. Four years had elapsed between this event and the discovery of fission, seven had passed since the discovery of slow neutrons, ten since the discovery of the neutron. Such was the unprecedented speed of this work.

Even in this period so overloaded with work, Fermi did not completely neglect his teaching activity. Instead of teaching classes or his private seminars, as in the past, he taught his co-workers during the work and many of them still remember with pride and pleasure the period of apprenticeship under Fermi's guidance. Once he had reached the main goal of the Chicago Project, Fermi typically enough, left to others the further development work in order to start something new and to lend his help where the difficulties were the greatest: at the time at Los Alamos.

The assignment of that laboratory, ably directed by J. R. Oppenheimer, was to make an atomic bomb with either U^{235} or Pu^{239}, as soon as they were delivered by other branches of the Project. The difficulties of this assignment were far from trivial; actually, at the beginning, nobody knew how to build an atomic bomb at all. Fermi did not have any specific scientific duty nor was he assigned any particular administrative responsibility; he was on the governing board of the laboratory with which the director consulted on all important matters, but otherwise he was a sort of oracle whose job was to solve problems above the ordinary capabilities of the staff, distinguished as it was. J. von Neumann, as a consultant, had a somewhat similar job.

Among the various activities at Los Alamos, Fermi took a direct interest only in the water boiler, a homogeneous reactor which had been built there; but in general he participated in all novel or unusual problems. I remember having listened in his office to discussions on hydrodynamics with von Neumann. They took the strange form of a competition in front of a blackboard to see who could first solve the problem; von Neumann, using his insuperable lightning analytical skill, usually won. Occasionally, such discussions could be interrupted by unexpected events. For instance, during one of these hydrodynamical sessions I once witnessed the arrival of a first class electronics expert who was confronted with a new and very difficult problem in circuitry. Within about twenty minutes Fermi concocted a circuit which would have solved the problem, but no one knew whether a tube with the necessary special characteristics even existed. Consultation of a tube manual disclosed that the required tube was really available and the apparatus was promptly built and worked satisfactorily.

The time in which the first atomic bomb would be ready for a test at Alamogordo was approaching. Several times we went to the New Mexico desert for preparations. Finally, shortly before daybreak on July 16, 1945, after a stormy night, we saw the light of the first atomic bomb. From a distance of about ten miles, through very dark glasses, we saw the blinding light of the explosion, an imposing and awful sight. The problem of measuring the energy release was immediately although crudely solved by Fermi. With the help of some confetti which he dropped, he measured the displacement produced when the front of the shock wave reached his observation point. Within a few hours, Fermi went with a tank to the crater of the explosion in order to measure the radioactivity of the sand.

That explosion signified in a way the end of the initial phase of the Los Alamos project. The major technical assignment had been accomplished, too late to influence the war in Europe in the decisive way that had been planned. Germany capitulated on the very day on which at Alamogordo we exploded a tremendous pile of ordinary explosives in preparation for some tests to be performed on the atomic bomb, which was expected to be ready in a couple of months. President Roosevelt had died suddenly in April and could not see the end of the enterprise he had so effectively fostered.

The success of the Alamogordo test was promptly communicated to President Truman, then at Potsdam in conference with Churchill and Stalin. The grave decision on the use of the bomb rested with the President. As usual, for serious policy decisions in the U.S., even before the success of the Alamogordo experiment, the President had appointed a restricted advisory committee, called the Interim Committee to counsel him on the employment of the bomb and on other matters pertaining to nuclear energy. Its recommendations had a purely advisory value because the final decision, according to the U.S. constitution, rested with the President as Commander in Chief. Earlier, several scientists who had been very active in the Manhattan Project, wrote eloquent pleas to the President recommending against the military use of the atomic bomb. Among them I might mention James Franck and Leo Szilard, who were particularly worried by the war use of atomic energy. Naturally, all this occurred in secrecy, without public knowledge. The Interim Committee appointed as scientific consultants A. H. Compton, Fermi, E. O. Lawrence and J. R. Oppenheimer. In a meeting held at Los Alamos about June 15, 1945, after long and painful deliberations, they recommended the military use of the bomb. This happened at Hiroshima and Nagasaki.

At the beginning of August, Japan surrendered, and thus ended the Second World War. The scientists at Los Alamos once again started to think about peacetime research, and there were many projects floating in the air. During the fall, plans for the future were taking shape. Fermi was still on a leave of absence from Columbia University, but just at that time the

University of Chicago planned to form a nuclear institute (the present Enrico Fermi Institute for Nuclear Studies) and repeatedly offered Fermi a position as its director. He absolutely refused a job that would have given him too much administrative work; fortunately Professor S. K. Allison, a distinguished scientist, a very able administrator, and a good friend of Fermi was appointed director. He supervised all the activities in the initial phases of the Institute and kept the job until after Fermi's death.

During the clear autumn days of Los Alamos, with the pressure of work relaxed, we resumed our old pastime of taking long walks, especially attractive in those beautiful and wild surroundings. Plans for the future were frequently our subject of conversation, sometimes in earnest, sometimes in a lighter vein. Among those that Fermi mentioned frequently was that in his mature years he would retire to a small college, with teaching duties only, and then write a book dealing exclusively with those theorems which are reputedly " well known " or " easily shown " and for that reason never really proved. He even began a list of such topics, but unfortunately the book was never written. For the immediate future, while the new, extraordinarily powerful neutron sources could have attracted Fermi to the exploitation of these new technical means in the neutron field where he was – as said before – the foremost world authority, he quoted instead, jokingly, a motto which he attributed to Mussolini, although probably it originated with D'Annunzio: " O rinnovarsi o perire " (Renew oneself or perish), and said that henceforth one had to turn to new chapters of physics in which the future lay. True to his word, when he returned to Chicago he worked on neutrons for a relatively short time, long enough to obtain brilliant results which themselves became starting points for a long series of investigations, but he immediately started to prepare himself for the new meson physics which was just beginning to develop.

In the last months of his stay at Los Alamos he also started to develop a keen interest in electronic calculating machines. In his Roman days, he had used a small mechanical hand calculator to compute numerically the ψ's (cf. paper N° 43) and in order to perform several other applications of the Thomas-Fermi method of calculating atomic properties. Numerical problems and numerical analysis were completely familiar to him and he recognized at once that the new powerful electronic computers, strongly advocated by von Neumann, were opening up new and unpredictable possibilities. The powerful computers at Los Alamos always had a strong attraction for him, and he experimented and worked with them for several summers. The problems connected with nuclear fusion had also interested him deeply. Already in 1946, he had reviewed them in a lecture course at Los Alamos in which he expounded many novel and original ideas.

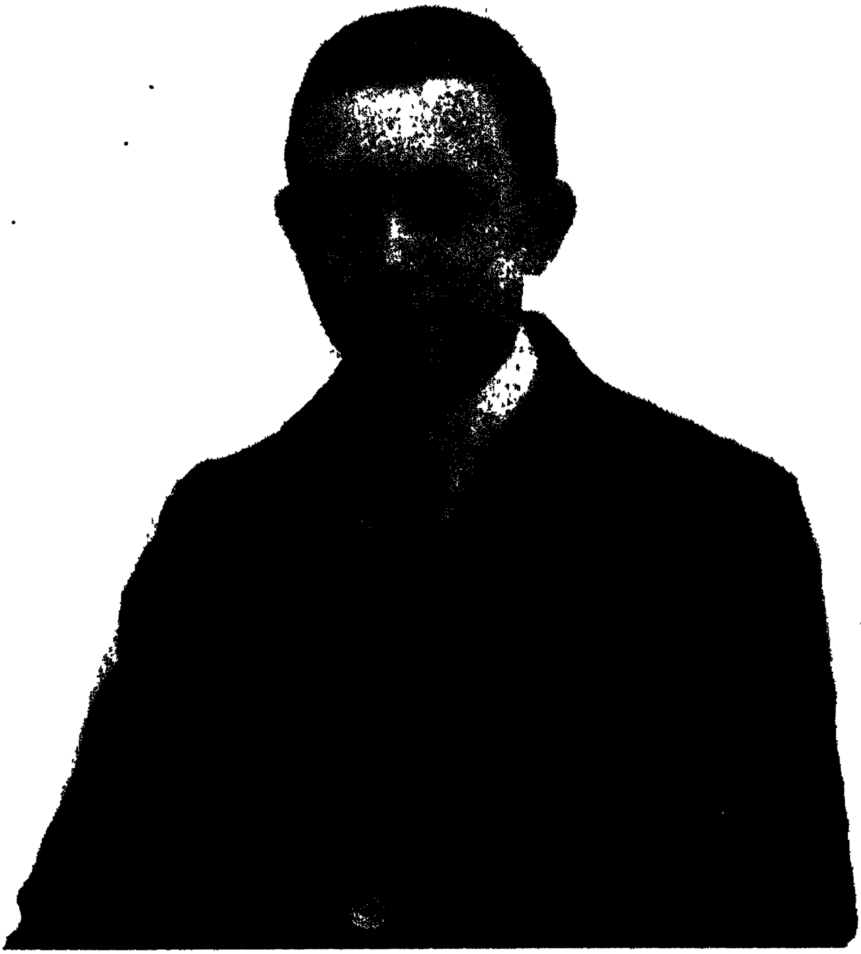
On his return to Chicago, while waiting for the synchrocyclotron and the new Institute to be finished, he again worked with neutrons at the Argonne Laboratory, using the pile as a source. We see in this period the conclusion of the investigations on neutron diffraction and on the scattering length, the origin of which can again be traced back to the Roman period. At that time he also sought to re-establish a system of instruction somewhat similar to that used in Rome. He had a new group of young pupils, most of them returning from Los Alamos, where they had worked in the theoretical group of Bethe, in the experimental group of Segrè, or in other groups. We shall mention among them Agnew, Chamberlain, Chew, Goldberger, Rosenfeld, Woods, and, somewhat later, a new arrival from China, Yang. At Chicago Fermi took a very active part in all seminars and in many discussions; often, with a single remark, he sowed the seeds of further important developments. For instance, Maria Mayer in her classical paper on the shell model (" Phys. Rev. " 75, 1969 (1949)) generously acknowledges: " Thanks are due to Enrico Fermi for the remark ' Is there any indication of spin-orbit coupling? ' which is the origin of this paper ". In the meantime meson physics was developing and Fermi immediately recognized the importance of the Conversi-Pancini-Piccioni experiment which he was the first to interpret correctly. But by now the Chicago synchrocyclotron was about to work and in Berkeley it had already been shown that such a machine was a powerful artificial source of mesons. Thus we enter the last phase of Fermi's experimental work; this is a series of important investigations on the pion-nucleon interaction performed with Anderson and younger pupils, such as Rosenfeld, Orear, Yodh and others. It was at this time that they coined the new words, pion and muon, for π–meson and μ–meson.

In this last period, Fermi, who by now was no longer fond of long trips, spent his summer vacations at Los Alamos or at Brookhaven, a most welcome guest of these Laboratories, especially of the first, to which he was particulary attached. He also spent a summer in Berkeley and he attended all the High-Energy Conferences in Rochester. Wherever there were new physics problems and young physicists you were likely to see Fermi arrive, always ready with some new and fruitful idea, and also ready to receive information, challenge and inspiration from his younger colleagues. In this period we also note a change in Fermi's methods of keeping up with scientific developments. He read less and less and relied more and more on conversation and oral sources of information which were always plentiful. Many active physicists enjoyed and profited from discussing their problems with him and on his side he took notes of these conversations and inserted them in the artificial memory, which by now was very bulky and elaborately cross-indexed extending to all of physics. On the other hand, he barely glanced at the journals and completely stopped reading any physics books. He once said that Weyl's book on group theory and quantum mechanics was the last physics book he read. His old friends also noticed a contraction in the span of his interest. Even for him it was becoming impossible to keep up with all of physics. He began to limit himself to high-energy nuclear physics and to his direct research interests. He still kept in reserve his powerful resources for other branches of physics, if they became necessary, but he did not seek new ventures far afield.

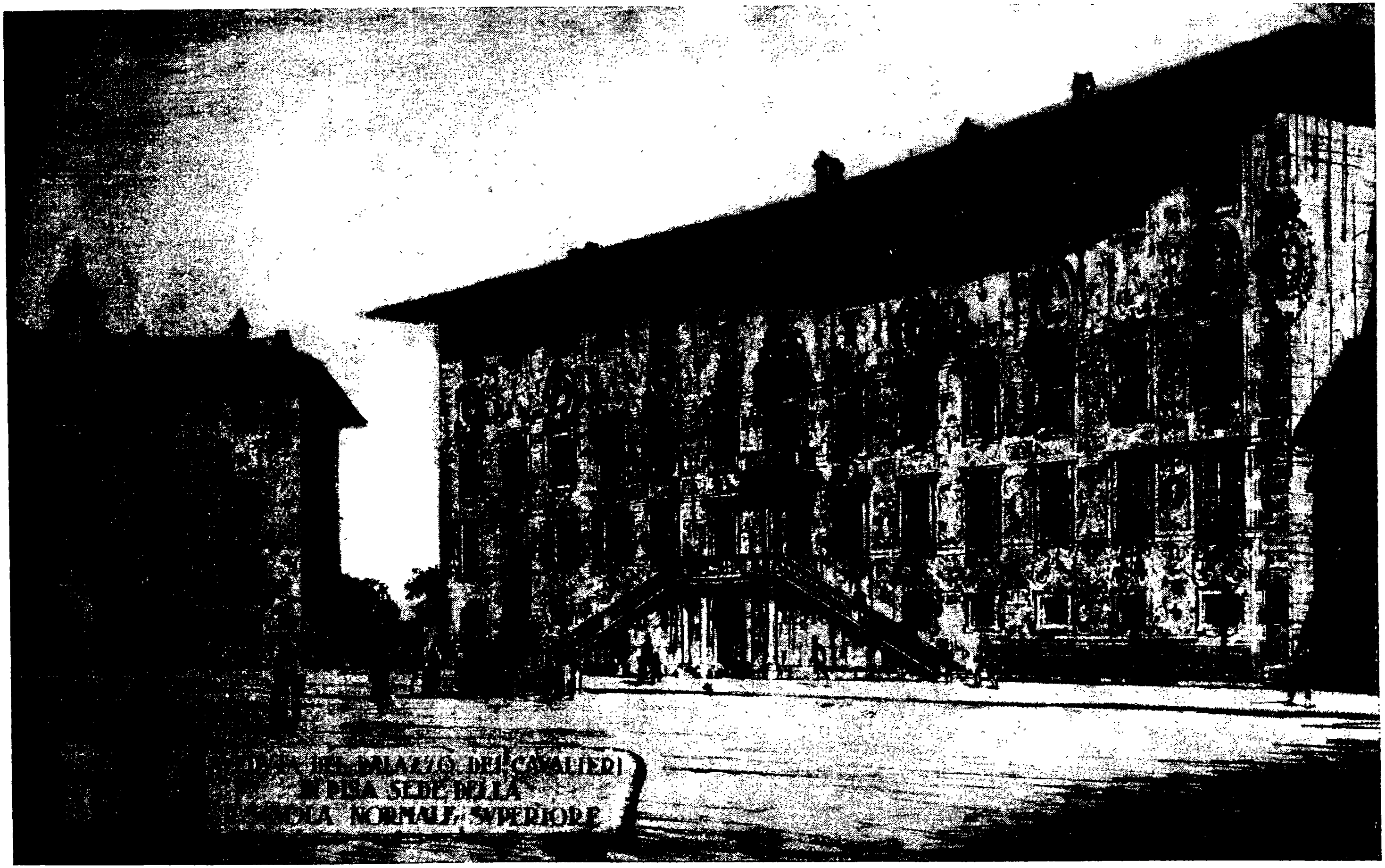
Again he often spoke about what would happen with the passing years when old age would set in, but it is typical and meaningful that in 1946, at the end of the Los Alamos period, after a few minutes of reflection, in seriously estimating the work accomplished and the path of the future, he used the number 1/3, meaning that up to then he had accomplished about 1/3 of what he hoped to accomplish during his whole life. That the problem of aging was present to him, even if it did not worry him, is apparent from many conversations. In one of the last ones before he fell ill, I was telling him about some experiments on proton polarization that we had recently performed in Berkeley. He commented that they gave me the right to do nothing for about five years, without being labelled " senile ", because after a piece of work of some importance one had the " right " to stop producing new research for some time before one had to be classed as a " retired " or " finished " scientist.

In his last years I also noted an extreme desire to avoid any waste of time, almost as if he had forebodings that time would be his most precious commodity. He worked and behaved as if he now had an obsession to avoid squandering time or energy, or wasting any of his possibilities. He acted as if he had a task assigned, a goal to reach.

In 1954 he fell ill in an insidious form. In the summer, with an effort of his iron will, he still went to Europe, made some mountain trips, and gave a beautiful course on pion physics at the summer school in Varenna, but by now his health conditions were clearly alarming. He returned to Chicago in September and submitted to an exploratory operation to diagnose the nature of his illness, which had remained obscure despite repeated examinations. Unfortunately, the operation could only recognize a hopeless situation. Fermi realized this immediately and accepted it with Socratic serenity. I believe that neither the members of his family, nor the friends who visited him during his illness, will ever forget the deep impression they received from his conversation at that time. He died on November 29, 1954, shortly after his 53rd birthday. He gave to science all he had and with him disappeared the last universal physicist in the tradition of the great men of the 19th century, when it was still possible for a single person to reach the highest summits, both in theory and experiment, and to dominate all fields of physics.



Enrico Fermi at the age of 17.



The "Scuola Normale Superiore" at Pisa.