Enrico Fermi in South America
and his Lectures in Buenos Aires

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Abstract

In 1934 Enrico Fermi accepted an invitation to deliver lectures in Argentina, Brazil and Uruguay. He arrived in Buenos Aires on July 30, lectured in Buenos Aires, Córdoba, La Plata and Montevideo and then moved on August 18 to São Paulo via Santos and Rio de Janeiro; he traveled back from Rio to Naples on September 1st. His visit had a large resonance, and halls were crowded despite the fact that he lectured in Italian. The University of Buenos Aires recorded his five lectures and transcribed them in Spanish; these are however not included in Fermi’s Collected Works edited by the Accademia dei Lincei in Rome and by the University of Chicago. In this paper we present Fermi’s five lectures in Buenos Aires, translating them in English for the first time.
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Enrico Fermi (Rome 1901 - Chicago 1954) has been one of the most important physicists of history both for his contributions to theoretical and experimental physics. Graduated in 1922 at the Scuola Normale di Pisa discussing a thesis on X-rays, in 1925 he was appointed professor of mathematical physics in Florence. In 1926, he invented the so-called Fermi-Dirac statistics that describes the energy distributions of semi-integer spin particles, such as electrons, protons, neutrons and other particles today generically called fermions. Thanks to this work he was assigned the chair of theoretical physics in Rome, the first in Italy. In the autumn of 1926 he moved to Rome in the Institute of via Panisperna, where he began the most fruitful period of his scientific life, and soon created a group of collaborators (Rasetti, Segrè, Amaldi, Majorana, Pontecorvo). The via Panisperna group initially dealt with atomic spectroscopy and later with the study of the atomic nucleus. Between 1933 and 1934 Fermi elaborated the \( \beta \) decay theory, based on the formalism of the quantum field theory and on the physical hypothesis advanced by Pauli that a neutron in the nucleus decayed into a proton, an electron and a neutrino (term invented by Fermi). His theory highlighted for the first time the existence of a new force, today called weak interaction. In 1934, hearing of the discovery of radioactivity caused by bombarding stable nuclei with \( \alpha \) particles (He ions), he began a series of experiments on the disintegration of nuclei using neutron sources produced in radon-beryllium lamps. The neutrons, being neutral, proved more effective than the \( \alpha \) particles for penetrating nuclei and breaking them, and Fermi discovered thirty new artificial radioactive nuclides. In particular, he discovered the great effectiveness of slow neutrons (obtained by colliding fast neutrons with light nuclei) in producing nuclear reactions. In 1938 he went to Stockholm to receive the Nobel Prize, awarded for his fundamental works on neutrons, and from there he moved on to the US where he settled. In 1939 he became a professor in Chicago; in the same year he demonstrated that the secondary neutrons produced in the fission could in turn produce new fissions and give rise to a chain reaction with the release of nuclear energy at macroscopic level, and he designed the first nuclear reactor, which entered into operation in December 1942. He was one of the protagonists of the Manhattan project for the use of nuclear energy in the atomic bomb, and in 1944 he became an American citizen. After the war he devoted himself to theoretical studies on the physics of elementary particles [1].

Year 1934 was the *annus mirabilis* for Enrico Fermi [2], with many great discoveries, in particular the theory of \( \beta \) decay, which paved the way to the theory of electroweak interactions and to the Standard Model of particle physics, and nuclear fission, that will lead him to the Nobel prize in 1938 (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). In the same year Fermi accepted an invitation to deliver lectures in Argentina, Brazil, and Uruguay. He reached Buenos Aires on July 30 1934 onboard the Neptunia\(^1\) ship of the Cosulich company leaving from Trieste [3], but stopping

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\(^1\) An interesting coincidence: Fermi will discover a new element with atomic number 93, which is called,
also in Naples, where Fermi probably boarded. The most important Italian newspaper, *Corriere della Sera*, wrote about the visit on its cultural page (page 3) on July 24 [4].

According to the memories of his wife [5] Laura, Fermi could not break his engagement at the last moment to pursue experiments, no matter how absorbing and promising. Anyway it would have been a mistake to forego this trip, which proved most successful from all points of view. Sixteen days on placid seas took us to Buenos Aires.

Fermi was well awaited and received in Buenos Aires. The press gave large resonance to the arrival of the scientist (Figure 1), and the Fermi couple experienced a sumptuous hospitality. As Laura wrote [5], we lived the life of the elite for over three weeks. We were housed in the most modern and elegant hotel we had seen up to then. We took us for rides along the Río de la Plata, and up to the Paraná; they invited us into their theater boxes for the best shows and musical performances; they entertained us in their sumptuous homes with that proverbial Spanish hospitality, so hard on the guests’ digestive system, that makes a hostess place another guest in charge of keeping your plate full at a meal of five courses – we came to look forward to the rare occasions when, free of invitations, we could quietly skip a meal. A great testimony of interest in science was given to Enrico. Fermi held his lectures in halls that were crowded and overflowing at the onset and kept overflowing to the very end of his course, despite the fact that he lectured in Italian [5, 7]. Spanish and Italian have much in common; moreover, a good portion of the Buenos Aires population is of Italian descent [2].

The five lectures of Fermi in Buenos Aires were recorded by the University of Buenos Aires [8], but, strange enough, were not included in the *Collected Works* by Enrico Fermi [9]. The subjects were:

I. Characteristics distinguishing atomic physics from the physics of ordinary bodies.

II. The concept of measurement and its criticism.

III. The fundamental elements of nuclear structure (part 1).

IV. The fundamental elements of nuclear structure (part 2).

V. The artificial disintegration of the nucleus.

The transcription had been made in Spanish; we present in the appendix an English translation.

today, Neptunium (Np). He discussed about hints of this discovery during his 5th lecture in Buenos Aires.

2During the time in which Fermi stayed in Buenos Aires, the tenor Tito Schipa performed in Teatro Colon and the director Ottorino Respighi in Teatro Cervantes.
Figure 1: Article on the first page of the daily newspaper “Critica” dated July 30, 1934.
On August 11 at 18h Fermi gave in Córdoba a lecture on artificial radioactivity, similar to the last lecture in Buenos Aires (a summary is available in [10]), and later in Montevideo. Also in small Córdoba, the town of the many churches at the feet of the Andes, where the only Italian was a fencing teacher; in orderly, green-gardened, intellectual Montevideo lecture rooms were tightly packed [5]. A last Argentinean lecture on Radioactivity, Light and Cosmic Rays on August 17 in the University of La Plata is documented and a summary.

After reminding the ever increasing importance of the study of radiation, not only in the domain of physics but also of biology, Professor Fermi stated that for reasons of competence he would discuss only the physical aspect of the problem. He discussed briefly the development of studies on luminous radiation, that gradually lead to the knowledge of other types of radiation, not directly perceptible to our eyes, but that have a nature analogous to that of light. He then discussed the origin of the notable differences that exist in the physical and chemical effects of this radiation, proving the theory by which the frequency of the radiation is the key element for the production of various reactions.

He then reviewed other types of radiation consisting of very fast corpuscles. These can be classified according to the type of particle (electrons, alpha particles, neutrons, etc.) and according to their velocity. Dr. Fermi explained how, based on these elements, it is possible to understand their effects, their action consisting mainly in ionizing the atoms; he argued that most of the biological actions of the various types of radiation must surely, in the last analysis, be linked to side effects of ionization.

Finally, he addressed the problem of cosmic radiation, examining the main hypotheses that have been proposed to explain it. It is – he said – a radiation that, although of very weak intensity, thanks to the
is available [11]; it was held in the room Wenceslao Escalante of the Academia Nacional de Agronomía y Veterinaria, and chaired by the dean, doctor Zanolli, and by the president of the Instituto Argentino de Cultura Itálica, doctor Marotta. Also in La Plata many students, professors and ordinary people attended.

On August 18 Fermi left Argentina to Santos with the ship Northern Prince arriving on the 21st, and then to São Paulo, in whose surroundings the intense green of the tropical vegetation sprang from the bright-red soil that gives Brazil its name in an antithesis of colors seldom achieved by painters [5] and Rio de Janeiro. The period spent in Brazil, invited by the mathematician Theodoro Augusto Ramos, professor in the Escola Politecnica of São Paulo, is documented in [12]. Brazil was looking for help in starting a school in theoretical physics, and Fermi was functional to the call of Gleb Wataghin from Torino. We note that Fermi’s lectures in Brazil have not been transcribed.

Finally the staying in South America came to an end, and the Fermi family left from Rio to Naples on September 1st. We cite again the words of Laura [5]. We left South America happy to end an experience too rich to be stretched any further. Of good things one must not have too much, and, as the French say, one may tire of eating partridge every day. On boarding the boat that would take us from Rio to Naples, we met the composer Ottorino Respighi and his wife. (Figure 2). Fermi and Respighi, companions for all the trip, were discussing most of the time, with Fermi trying to extract information on a possible mathematical theory of music, and Respighi, according to Laura, smiling with condescension. The boat arrived in Naples during the second half of September; then Fermi’s wife went to rest in Florence at her aunt’s villa while Enrico went to Rome alone, where some of his greatest discoveries expected him, notably nuclear fission with moderated neutrons, for which he will be awarded the Nobel prize in 1938.

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enormous energy of the corpuscles that constitute it can sometimes produce disintegration phenomena of much greater magnitude than can be obtained in the laboratory.
Lecture I
Characteristics distinguishing atomic physics from the physics of ordinary bodies (Buenos Aires, August 2, 1934)

First, I would like to express my deepest gratitude to the Argentinean Institute of Italian Culture and to its President, Engineer Marotta, for the high honor and the great pleasure they have given me when they invited me to come to Buenos Aires. I would also like to thank the Faculty of Exact Sciences and its Dean Engineer Butty, and Engineer Selva, and Professor Isnardi, for the kind words they said in my regard. It is a real pleasure for me to get to know this country, where so many of my compatriots have found a new homeland, as well as to have the opportunity to meet personally the Argentinean colleagues of whom I only knew the works through publications.

In this conference, I will deal with the development of our knowledge about the theory of the structure of matter. The problem of the structure of matter has been proposed since the origins of scientific thought, although its true development has been carried out mainly at the end of the last century and has taken in our century a form that could be called explosive. Physical science is probably as old as human thought and probably arose due to two different motivations: a rather practical one, which puts itself at the service of concrete and immediate ends, and another, more speculative, of satisfying curiosity. These two tendencies are mixed from the beginning in physics, as well as in other sciences. Geometry, for example, is in itself one of the most abstract parts of mathematics, but its name indicates that it originated from a practical problem: the measurement of the land.

Since ancient times we have evidence of science whose motive was scientific curiosity, astronomy being the most characteristic example; while in the field of physics especially mechanics, which is a practical science, developed in ancient times. But next to mechanics we find the first attempts at speculations not linked to the desire to obtain concrete results. It is sufficient to recall the investigations of the school of Democritus of Abdera, who, for the first time, spoke of the “atom” when building his atomic theory. He came to this concept guided by the observation of the compressibility of bodies. His way of reasoning was as follows: unable to conceive that matter without cavities could vary in volume, and seeing that most bodies could vary in volume, he deduced that there were interstices in their structure and that matter was constituted by particles (atoms) separated by gaps. When matter is compressed, the various atoms that constitute it get closer; when it expands, they separate. Naturally, it took many centuries of thought and scientific work before the conception of Democritus could reach more important conclusions; this idea should be considered as a great intuition for his time, if you keep in mind that it was reached with a truly scarce experimental base.
After Middle Age, in the Modern Age the real development of science begins. Even here we can see that the first sciences developed were those that have as their object the phenomena that most directly impress our senses: mechanics and optics, and later, the science of heat. The last to develop was electricity, probably because electrical phenomena were the least prominent. It is known, for example, that in the open air there is a fairly considerable electric field, which however escapes entirely our senses and although there are other electrical phenomena that are very apparent, such as lightning, they obviously do not adapt to being taken as starting point for a science. All this explains why the study of electricity has developed late, in the last century. In the study of electricity we also find the collaboration of several trends, some speculative, other experimental or technical, which culminated finally in a set of concrete and useful results for the needs of mankind. The most prominent example is radio communications that made such brilliant technical progress in our century. This is also a case of great practical importance, originated from a purely speculative field: Maxwell, summarizing the results of electromagnetism, established equations that he later managed with purely mathematical means and found that there is the possibility that electromagnetic waves propagate. In his speculations he did not go beyond the ultra-theoretical field. The second stage in which the experimental phase entered is that of Hertz, who took up Maxwell’s works, experimentally demonstrating the existence of the waves theoretically foreseen by this physicist. The last stage is that of Marconi, a more practical spirit than the other two, who wondered: what can these waves do? Under the conditions established by Hertz, waves could not travel a distance greater than a few meters; Marconi tried to go further and take advantage of them to transmit signals. Theorists said to Marconi: think to the fact that Earth is curved, and therefore you can only telegraph as far as the waves can go directly, and not beyond. Marconi was not a theoretician, and these objections did not worry him excessively. He moved on and made transmissions as far as waves are sensible, so far away that theorists affirmed that it is not possible putting their hands on their heads. A circumstance had been ignored: the existence of a conductive electrical layer in the atmosphere, which encloses the atmosphere in which we live, between two surfaces: the surface of the Earth and that outer layer separated from it with a very small distance compared to the radius of the Earth. When waves are transmitted in this layer, they are forced within this layer, and they can reach the antipodes. We have therefore started from mathematics and then, through physics, we came to the technique.

Encouraging science, even the most abstract one, tomorrow’s techniques are prepared. Of course the promotion of science is a long-term capital investment, because experience shows that technique follows a long way from scientific results; but in the life of nations, investments can be made over very long terms.

Let us now return to the origin of atomic theory. If the argument for the existence of atoms were only Democritus’ compressibility, this hypothesis would certainly seem very dubious. On the other hand, modern science has accumulated today such a number of facts in its favor that doubting about it is no longer rationally possible. These facts have
been found only in modern times, when chemistry ceased to be alchemy and became a quantitative science, freeing itself from the prejudices that obscured its birth. Chemistry thus managed to establish the laws of multiple and defined proportions. These laws are interpreted in the simplest way, admitting that there are some fundamental substances, the chemical elements, and that each of these substances is made up of very small units, so small that they can only be seen in large quantities. Then, the molecules of the innumerable compound bodies are formed by taking determined numbers of these fundamental units of each element.

In this atomic chemical approach an element is still missing that serves to fix the absolute size of the molecules. Molecules and atoms are not visible: they are of submicroscopic dimensions, surely smaller than one tenth of a thousandth of a millimeter. If only chemistry existed as the basis of the atomic approach, a criterion would be lacking to specify how much smaller the atoms actually are than the preceding limit, but atomic conception is also reached by another route, which is precisely the study of properties of gases.

The molecular kinetic theory of gases gives a truly simple and convincing explanation of the properties of gases themselves, and in particular of their tendency to expand. If the gas is made up of a large number of continuously moving corpuscles, they will invade all the regions that are free at their disposal. In this kinetic theory of gases we find for the first time an argument that allows us to determine the molecular dimensions. The internal friction of the gas depends on the molecular dimensions, in such a way that the measurement of either quantity implies the measurement of the other. The dimensions found with this and other equivalent methods are very small. To get an idea, you can imagine an ammunition of diameter 2/3 of a centimeter enlarged to the dimensions of the Earth, keeping its structure unchanged: an atom would be the size of the ammunition.

Sometimes we are forced, intuitively, to consider as real only what we can see or feel directly. Given the smallness of their dimensions, we can never hope to see molecules. In fact, although you can think about perfecting the microscope technique, you will never be able to clearly distinguish objects with dimensions less than the wavelength of light, which, although small, is thousands of times larger than the atom. Nevertheless, if you can’t see atoms with ordinary light, you can study them with X-rays that are nothing but light of a different color. They allow, if not to see in the material sense of the word, at least to do something similar.

With the experience of Laue and the Bragg on the structure of crystals, it was indeed possible to accurately recognize the position of atoms and molecules in a crystalline body as if objects were viewed under a microscope. The image of a gas that results from the kinetic theory is something very disordered: the molecules collide irregularly with each other and

\footnote{This is probably transcribed badly in the Spanish text. Such a proportion exists, with an accuracy of an order of magnitude, between the radius of the nucleus in the Rutherford model and the inter-atomic/intermolecular distance; the discussion on the nucleus is however presented later in the lecture (note of the editors).}
against the walls, describing very complicated movements, so it may seem strange that the gas as a whole obeys simple and very precise laws. The reason for this simplicity must be sought in the fact that the molecules are in very large numbers, so that in all the phenomena in which the properties of a set are studied, the individual irregularities disappear on the average. This regularization of the laws relating to a very large group is a completely general phenomenon of mathematical nature. Just as we find regular laws in the statistics of molecules, we can find them in the statistics of a social or economic phenomenon regarding the properties of a large population. From parents to children we find fluctuations in height of a completely irregular nature, which have the appearance of escaping all laws, but if we take the average height of a people we find that individual fluctuations disappear. We can find variations in height, but the phenomenon will be justifiable with the variation of economic conditions or variations in climate: the average destroys all the capricious individual variations.

The quantitative study of the properties of a gas through the analysis of the behavior of each molecule is a mathematically insoluble problem. However, statistical mechanics forgoes the search for such a solution and accepts as a valid alternative the average properties of a large number of molecules. These average properties determine the behavior of a gas as we observe it. Sometimes the irregular movements are observed under the microscope. If very small colloidal particles are observed microscopically, it will be seen that they are in continuous agitation. If we observe a large body in the calm air, we will see that it remains still, because it receives shocks on its entire surface that push it in all directions, canceling their effects on average, so that the body remains immobile. However, if the body is small, the number of the shocks are not so great and therefore you can perceive slight differences in the intensity of the shocks in one direction or the other, which produce a visible agitation of these corpuscles. These movements take the name of Brownian movements.

Knowing the existence of atoms, the question arises naturally of whether these corpuscles should be considered truly indivisible, as in the classical conception, or if they possess a complex structure. A question of this kind could not be discussed except on the basis of experiences and the first experiences that could have made us suspect the existence of an internal structure of the atom were made in the second half of the last century. The phenomena of electrolysis, on the one hand, demonstrate that, in certain circumstances, atoms can give rise to ions electrically charged, a fact that indicates the presence of electrified corpuscles inside. The existence of these subatomic charged corpuscles is more directly evidenced by the study of electrical discharge in rarefied gases, and particularly in the study of cathode rays. These turned out to be a projection of corpuscles of extremely small mass and of negative electrical charge, which were called electrons and that intervene as a common constituent in all atoms. Indeed the same electrons with the same negative electrical charge and with the same mass are obtained from all different substances on Earth; they are also equal to the corpuscles emitted sometimes in large swarms by the Sun, which colliding with the Earth’s atmosphere give rise to the phenomenon of the Northern Lights.
The electron has a negative electric charge; matter, being electrically neutral, must also contain a positive component. The investigation of the nature of the positive constituent gave rise to many discussions. At the beginning of this century, Thompson’s theory was in vogue; this theory modeled the atom as a sphere of positive electricity containing negative electrons, which when describing complicated movements would give rise to light phenomena. This conception was soon replaced by another, which is in some sense the antithesis of the previous one, due to Rutherford, who assumed the positive electricity of an atom gathered in a corpuscle of dimensions much smaller than those of the atom, having given this corpuscle the name of nucleus. Rutherford came to this conclusion thanks to famous experiences based on the following principles. Radioactive bodies spontaneously emit alpha particles among their radiations, which are electrically positive corpuscles of such a great velocity that they can pass through thin layers of matter, before being stopped by crashes against atoms. The alpha particle being charged with positive electricity is repelled when the positive charge of an atom is approaching, thus deviating its trajectory; a strong deviation occurs only when the particle passes very close to the charge itself. The frequency with which deviations in the trajectories of the alpha particles are observed, naturally depends on the distribution of the positive charges, the deviations being more probable at large angles the more concentrated the positive charge is. Comparing the results of the observations on the frequency of the deviations of the particles with theoretical predictions corresponding to several hypotheses on the distribution of positive electricity, Rutherford concluded that the best agreement between theory and experience is obtained by assuming that the positive charge of the atom was all concentrated in its center. The atom is therefore constituted by a positive nucleus located in the center, around which electrons move. These electrons exist in sufficient number to neutralize the positive charge of the nucleus with their negative charge. This model of the atom is analogous to a tiny planetary system, in which the nucleus corresponds to the Sun and the electrons to the planets. If the nucleus has, for example, charge +7, seven electrons, each one of charge -1, are needed to neutralize it. This results in the enormous importance of the charge of the nucleus in fixing the properties of the atom, since the number of electrons that form it depends on it. If the nucleus has a charge +1, the neutral atom contains only one electron, being that of hydrogen; if it has a charge +7 it is neutralized by 7 electrons, constituting the nitrogen atom; a nucleus of charge 92 with 92 electrons forms the uranium atom.

The model of the atom as a planetary system that we have just described is the one that is still supposed to be correct today, and has suggested for some time that the treatment of atomic physics problems could be done with the same methods of celestial mechanics following the success they have had in astronomy to explain the movement of the planets. Experience, on the other hand, has shown that such a simple solution is not possible. The laws of classical mechanics have been obtained from experiences carried out partly on bodies of ordinary dimensions and partly directly on objects of very large dimensions, such as planets and stars. Pretending to apply without modification these same laws to a
corpuscle of the dimensions of the atom undoubtedly constitutes a rather risky extrapolation and one should not be surprised if it leads to failure.

In the next conference I will try to give an idea of the changes that have been introduced in the classical laws of mechanics in order to build a new mechanical theory appropriate for the treatment of problems related to atoms.
Lecture II
The concept of measurement and its criticism (August 6, 1934)

In the last lecture I tried to give an idea, I would say, about the anatomy of the atom, that is about the structural elements that constitute it. In this second general lecture, I will try to give an idea of the laws that govern the movement of the constituent elements of the atom and thus determine the physical and chemical properties of matter.

Summarizing what I said on the last time, I remember that we had come to describe the Rutherford model, according to which the atom is constituted by a positively charged central nucleus, in which almost all the mass is concentrated, and a number of electrons that move around it with a complicated movement. The number of electrons is determined by the magnitude of the charge of the nucleus: being the atom neutral, it must have as many electrons as needed to neutralize the positive charge of the nucleus. Then I announced the problem of the investigation of the laws according to which the movement of electrons occurs and which determines the properties of the atom.

From the first attempts to quantitatively study the behavior of the atom, it was recognized that the ordinary laws of mechanics and electromagnetism could not be applied to it. The reason is extremely simple: it results from the general principles of electromagnetism that, when an electric charge describes a movement that is not rectilinear and uniform, it radiates electromagnetic energy; and the electrons in an atom describe precisely movements with acceleration. The phenomenon is analogous to the irradiation of radiotelegraphic waves, produced by an alternating current that travels through the antenna. However, oscillatory motion electrons emit energy and the amplitude of their vibrations is rapidly extinguished because energy is lost, radiated in the form of electromagnetic waves.

According to classical electromagnetism, while traveling in an orbit an electron in an atom radiates energy and therefore its own energy decreases; this fact would translate into a continuous decrease of the radius of the orbit, after some time the electron would end up falling into the nucleus. It follows that if the same laws of mechanics and electrodynamics of macroscopic bodies were valid for the atom, we could not understand how the atom could maintain its existence and how the electrons could continue to rotate around the nucleus without falling into it. It is then concluded that the classical laws are not valid (as we had suspected), and therefore they should be modified. Here comes the problem of looking for the laws that must replace the old invalid ones.

The beginning of a solution to this problem, although provisional, appeared in 1913 and was due to the Danish physicist Niels Bohr, who based his research on the concept of the “quanta” of energy, introduced in physics in the study of thermal radiation.
By studying this problem with the instruments of classical mechanics and physics, a disagreement was reached between theory and experience, analogous to that found by classical mechanics applied to the atom. Numerous attempts were made to tweak the laws and try to overcome that inconvenience. Planck proposed a successful solution based on a hypothesis that must have seemed very strange and daring to the physicists of its time. The principle is as follows. In a mechanical oscillator, the energy of motion according to classical mechanics can vary continuously from zero to infinity; Planck, on the contrary, supposes that physical reality is different, and that the energy of an oscillator can only take integer, discontinuous, multiple values of a certain energy, called the “quantum” of energy. He also conjectures that between this minimum degree of energy and frequency there is a proportionality relation: \( \varepsilon = h \nu \), where \( h \) is a universal constant independent of the special properties of the various bodies. This constant is called the Planck constant.

I believe that Planck himself, in the early days, did not believe to the letter in this hypothesis, but rather considered it as having a heuristic value, probably without a correspondence to physical reality. However, Planck was able to demonstrate that by accepting this granular structure of energy, the difficulty of interpreting the spectrum of incandescent bodies was resolved.

The second application of quantitative concepts came a few years later, that is, in 1905, and was due to Einstein, who used it to interpret the photoelectric effect. He admitted according to Planck’s ideas that the energy of light is not distributed throughout the light wave, but concentrated in energy granules, or in packets having each an energy content \( \varepsilon = h \nu \); these granules were called “quanta of light.” Such a conception, which represents in a certain sense a return to the corpuscular theory of light, allows us to interpret how a very weak illumination can determine the expulsion of electrons from different bodies, provided that the frequency of light is large enough to deliver sufficient energy to an electron to overcome the attractive forces that bind it to matter, when the atoms constituting this matter absorb a “quantum” of energy.

The introduction of the notion of the quantum of light, which, as we have said, represents a return to corpuscular theory, seemed for a long time to be in direct contrast to the whole complex of phenomena that has led to admitting the wave theory. We will see at once how the contrast is only apparent and how modern theories allow us to give a unitary interpretation of the diffraction phenomena and of those in which energy changes occur by “quanta”.

Let us now return to Bohr’s theory on the structure of the atom and, simplifying, let us refer to the simplest case of the hydrogen atom, consisting of a nucleus and of a single electron. The force that attracts the electron to the nucleus due to Coulomb’s attraction

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5Fermi is speaking here of the problem of the so-called ultraviolet catastrophe; it is not clear if there are omissions in the transcription. Classical physics predicts that an ideal body at thermal equilibrium emits radiation in all frequency ranges, releasing an arbitrarily high amount of energy. This would cause all matter to radiate almost instantaneously all of its energy, which is clearly a paradox (note of the editors).
is inversely proportional to the square of the distance and therefore obeys the same law of gravitational attraction exerted between the planets and the Sun. If the same laws of classical mechanics regulating the movement of the planets were valid in the atom, the movement of an electron should be equal to that of a planet except for the difference in dimensions. The electron’s orbit would therefore be an ellipse with the nucleus in one of its foci. If for simplification we limit ourselves to circular orbits, we find that because of the different radii that they can possess, the energy of the movement should be able to take continuous values, as well as the radii of the possible orbits could vary continuously from zero to infinity.

The fundamental hypothesis of Bohr’s theory is to suppose, as opposed to this result of classical mechanics, that not all mechanically possible states are actually physically achievable, and that the only physically achievable states, called “quantum states”, are a discrete succession of states selected with certain particular rules, indicated by Bohr, and which don’t need to be specified here. Bohr also conjectures that when the atom radiates energy, it abruptly passes from one quantum state to a different one, emitting the difference in energy of the two states in the form of radiation in one single quantum of energy.

These ideas by Bohr allowed to give a quite satisfactory qualitative interpretation of a whole complex of properties, especially spectroscopic, of various atoms. In no case, however, were these considered as a satisfactory solution to the problem of the atom, either because they are logically incoherent, or because they proved to be insufficient in many cases, for an exact quantitative description of the phenomena.

Consequently, there was a succession of attempts to determine on a more solid basis the physics and mechanics of the atom. After many failures, an atomic mechanics has been built based on a total revision of the same fundamental kinematic concepts and which can now be considered as a satisfactory solution to almost all of the atomic problems, except those related to the structural properties of the electron or the nucleus.

Without going into the mathematical details of this new atomic mechanics, I will try to explain which concepts have served as the basis for its construction.

With this aim, as in the theory of relativity, the starting point was the criticism of intuitive concepts that, under a rigorous examination of the concrete possibility of controlling them, are insufficiently defined. In the case of the theory of relativity, the starting point was the critique of the concept of simultaneity of two events, which led Einstein to recognize that simultaneity has no absolute value, but is relative to the system in which observations are made; this fact lead to the fact that two events that are simultaneous for one observer are not simultaneous for a different one.

In the construction of atomic mechanics, a criticism of the kinematic concepts of position and velocity of a material point was necessary. This criticism was developed by discussing the concrete possibility of making a measure of these two elements. It is necessary to understand that this criticism is not referred to the technical difficulties of the measurements. The main question here is the analysis of the limitations in the precision of
the measures, inherent not to imperfections of the instruments or the methods, but to the very nature of the phenomenon under examination. From this analysis it turned out that in the problems of atomic physics, it is not possible to avoid the disturbances that the action itself of the measure exerts on the phenomenon under examination. The criticism culminated in the so-called Heisenberg principle of indetermination, according to which there is, at least in principle, no limitation to the exact measurement of the position or speed separately, while a limitation exists for their simultaneous determination. In fact, a measure of the exact position necessarily produces a very large and uncontrollable alteration of the velocity, and a measure of velocity produces an uncontrollable alteration of the position.

The new atomic mechanics is often called wave mechanics, because one of its most significant mathematical forms consists in associating the movement of a material point with a system of waves analogous to the system of waves associated with the movement of a quantum of light. Thus, from a historical point of view, wave mechanics came through de Broglie and Schroedinger starting directly from this analogy and only later it could be shown that the wave scheme was mathematically equivalent to that proposed by Heisenberg, based on a criticism of the principle of measure.

In the new mechanics the “wave-corpuscule” dualism has found a harmonic interpretation since the two conceptions, both related to the case of light radiation and to the dynamics of a point, can be presented as two different aspects of the same phenomenon.

In the new mechanics, finally, there is the possibility of a quantitatively exact and logically unitary description of the entire complex of spectroscopic and chemical phenomenology, of which the early Bohr conceptions allowed only qualitative interpretations.

Of course, the validity of this new theory has also its limitations. Such limits are found when phenomena are considered in which the structure of the electron or that of the nucleus intervenes, that is to say when these bodies cannot be considered as point-like, and therefore their properties related to extension or internal complexity must be taken into account.

This opens a new series of problems whose main objective is to investigate the structure of the atomic nucleus.

In the next conference, we will review some of the main results obtained to date in this new field of physics.
Lecture III
The fundamental elements of nuclear structure, Part 1

In the physics of the atom, the structure of the nucleus is usually ignored, since this is considered as a material point, given its extreme smallness. This description, sufficient for most atomic problems, is obviously incomplete. The most convincing demonstration of this fact comes from radioactive phenomena, known since almost fifty years, which consist, as it is well known, in a spontaneous disintegration of the nuclei of the heaviest elements.

The data available on the various species of nuclei are, first of all, the electric charges, the value of which coincides with the atomic number when the charge of the electron is taken as unity, and the mass number. The latter always has values close to integers, measured with the ordinary unit with which the atomic weights are measured, taking into account the existence of the various isotopes.

These facts have allowed us to suppose that the various nuclei are made up of diverse aggregates of the same fundamental elements. Until a few years ago, these fundamental elements of nuclear structure were thought to be the two simplest particles hitherto known: the electron (of electric charge -1 and negligibly small atomic weight) and the nucleus of hydrogen, or proton (of electric charge +1, and atomic weight close to 1). By adding a convenient number of electrons and protons, it was always possible to obtain the necessary values for the electric charge and for the atomic weight of the nucleus. Thus, for example, it can be thought that the nitrogen nucleus, that has an electric charge +7 and an atomic weight 14, is made up of an aggregate of 14 protons and 7 electrons.

The fundamental elements that we can use to build a general diagram of the nuclear structure have increased today thanks to the discovery of two new corpuscles: the neutron that has zero electric charge and atomic weight close to 1, and the positive electron or “positron” that differs from the common electron only in the sign of its electric charge. Thanks to these discoveries, the ideas about the structure of the nucleus have currently undergone a considerable revision so that a new scheme is currently preferred to the previous one (a construction based only on protons and electrons). According to these new ideas, the fundamental constituents of all nuclei are protons and neutrons. The reasons for preferring this second scheme to the original one derive mainly from theoretical difficulties that make it hard to understand how light corpuscles can be maintained in a region of extremely small dimensions such as the nucleus. It results from quantum mechanics that, while there are no difficulties in understanding that relatively heavy corpuscles such as the proton and the neutron stay in the nucleus, admitting the fact that light corpuscles such as the electron or the positron can stay as well in the nucleus would require profound modifications of the fundamental laws.
Another type of difficulty depends on the fact that, if certain fundamental concepts of wave mechanics are also applicable in the nuclear field, the analysis of the nuclear spectra, for example, of nitrogen, establishes that the number of elementary corpuscles contained in the nucleus of this element must be even. If nuclei were formed by protons and electrons, the nitrogen nucleus should have 14 protons and 7 electrons, that is to say, in total, an odd number of corpuscles. On the other hand, if we assume that nuclei are formed by protons and neutron, a nucleus of charge +7 and atomic weight 14 is made with an aggregate of 7 protons and 7 neutrons, and therefore the number of constituent corpuscles is even. This evidence that we have illustrated with the example of nitrogen is present in other cases in which it is found that assuming a nuclear structure based on neutrons and protons solves the difficulties that would result from assuming nuclei made up of protons and electrons.

The discovery of the neutron was made in 1932, and is due to a series of works by the German Bothe, the French Curie and Joliot and the English Chadwick. Neutrons are released spontaneously and are projected with considerable energy by the nuclei of the light elements and particularly by beryllium, under the action of bombardment with $\alpha$ particles. Their characteristic properties and in particular their high penetrating power depend essentially on the absence of electric charge. Indeed the deceleration that a charged particle undergoes, for example, as it passes through matter, depends on the fact that as the particle approaches the electrons of the atoms it passes through, they exert electrical forces that set them in motion, thus determining the transfer to them of a part of the energy of the particle, which rapidly loses speed until immobilization. On the other hand, the neutron, having zero electric charge, only acts on other corpuscles when it approaches them at very small distances, and therefore the deceleration it undergoes when passing through matter is greatly diminished, thus, the penetrating power comes to be a few thousand times larger than for the $\alpha$ particle.

What is practically observed are collisions between neutrons and nuclei of matter that they cross through. On the contrary, collisions between a neutron and an electron are extremely rare, a fact that may seem strange given that electrons actually exist in considerably greater numbers than nuclei. The reasons for this fact, which would be difficult to understand with the concepts of classical mechanics, are found instead by studying the collision phenomenon based on wave mechanics. This leads to establish that the probability of collision between a neutron and a corpuscle is approximately proportional, neglecting other differences, to the square of the reduced mass of the system of the neutron and the colliding corpuscle. This reduced mass in the collision between a neutron and a heavy nucleus is close to 1, while in the collision against an electron it is equal to the mass of the electron itself, that is, $1/1800$. It follows, therefore, that the ratio of the probability of collision against a nucleus or against an electron is of the order of 1000 000, which certainly justifies the rarity of collisions with electrons.

In the same year 1932 in which the neutron was discovered, the existence of the new elementary particle of which we have already spoken, the positron, was also recognized.
The existence of positrons was recognized for the first time in secondary phenomena that accompany cosmic radiation. Although the nature of this cosmic radiation is still being discussed today, it has been experimentally proven that it contains corpuscles of energies up to a thousand times higher than those obtainable in the laboratory. The analysis of the sign of the electric charge of these particles can be carried out by examining the direction in which they deviate when they cross a magnetic field. It was precisely by photographing the trajectory of corpuscles produced by penetrating radiation in Wilson’s chamber that Anderson in California found for the first time indications of the existence of corpuscles whose traces, resembling for all the appearance of traces of electrons, were deflected by a magnetic field in the opposite direction to that of the electrons, thus indicating that the charge of the corresponding corpuscle was positive and not negative.

The most beautiful experiences in this field are due to English Blackett and Italian Occhialini. Using an ingenious device to be able to photograph with a Wilson’s camera a large number of corpuscles produced by penetrating radiation, these physicists could photograph extremely complicated decay phenomena, probably justifiable with the great energy of cosmic rays, in which from the same decay center it is possible to observe the radiation of a few dozen high-speed corpuscles. If the phenomenon is observed by applying a magnetic field to the Wilson’s camera, it can be recognized that some of these tracks belong to negative electrons, while others deviate in the opposite direction and must be attributed to positive electrons.

After the discovery of the positron, the presence of this corpuscle has also been recognized in some other circumstances reproducible in laboratory. In particular, it was discovered that, under the action of very hard $\gamma$ rays, pairs made up of a positive and a negative electron are produced from the same point.

The discovery of the positive electron can also be considered interesting because, before experience, theory had already made it possible to conjecture its existence.

We will see in the next lecture what is the theoretical importance of the discovery of the positive electron and what are the properties of this new particle.

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6The Wilson chamber [13], or cloud chamber, invented by C.T.R. Wilson at the beginning of the twentieth century, was an instrument for reconstructing the trajectories of charged particles. The instrument is a container with a glass window, filled with air and saturated water vapor; the volume could be suddenly expanded, bringing the vapor to a supersaturated (metastable) state. A charged particle crossing the chamber produces ions, which act as seeds for the generation of droplets along the trajectory. One can record the trajectory by taking a photographic picture. If the chamber is immersed in a magnetic field, momentum and charge can be measured by the curvature (note of the editors).
We had reviewed in the last conference the experimental discovery of the positive electron. This experimental result has also been a brilliant success for the theory, since some years before the discovery the possible existence of positive electrons had been conjectured based on theoretical considerations. Such conjecture was due to the English physicist Dirac; he arrived to it trying to build the wave mechanical description of the electron on bases compatible with the theory of relativity. The theory that he thus constructed seemed immediately very interesting, especially because without the need for ad hoc hypotheses, he realized the existence of a magnetic moment of the electron, which is necessary for the interpretation of the multiplicity of spectral lines of emission from atoms. Despite this success, Dirac’s theory had a serious drawback, since, in addition to predict a physical reality for electron [spin] states, it allowed other states for which kinetic energy had a negative value instead of a positive one and whose interpretation seemed mysterious in the early times. For example, for an electron not subjected to forces and with a momentum \( p \), the kinetic energy in Dirac’s theory has the following expression:

\[
L = \pm \sqrt{m^2c^4 + c^2p^2}.
\]

The states corresponding to the positive sign coincide with the ordinary expression of the kinetic energy of the theory of relativity, as it also includes the term \( mc^2 \), representing the energy equivalent to the mass of the electron. However, no possible interpretation was found to the negative sign of the radical, since it cannot describe the behavior of a material point. To solve this problem, Dirac proposed a hypothesis that seemed at first quite strange: he admitted, in effect, that all the states corresponding to a negative kinetic energy should be considered occupied in the sense of the Pauli exclusion principle, which gave a direct explanation of why it is impossible, at least under normal conditions, that an electron goes from a state of positive energy to one of these abnormal states. According to this conception, the physically empty space should be considered corresponding to the case in which all infinite states with negative energy are occupied by one electron each, while those with positive energy are all free.

In Fig. 1, the states are schematically represented by horizontal lines; the ones with positive energy extend above \(+mc^2\) and the “negative” ones below \(-mc^2\). Indicating with a dot that the state is occupied by an electron, the empty space is schematized by the situation represented by \(a\). On the other hand, in case you have a single electron, it is represented by \(b\): all negative states are occupied as also a positive one. Conversely, case \(c\) represents the situation in which all positive states are free and negative states are all occupied except for
Fig. 1

one, or in other words, there is a gap in the negative distribution. It can be recognized that the physical properties corresponding to this gap are identical to those of an electrically charged corpuscle of opposite charge to that of the electron, that is, that the gap behaves like an electrically positive corpuscle because it corresponds to the absence of a negative electron in the place of the “hole”. At first Dirac thought that these gaps behaving like electrically positive corpuscles should be identified with the protons; however this idea had to be abandoned later, because it was shown that even taking into account the electrical interaction between all the electrons, it always turned out that a normal electron and a gap necessarily have the same mass, whereas the electron and the proton have very different mass. The experimental discovery of the positive electron has simply allowed us to interpret these new corpuscles as gaps in Dirac’s theory. Other important properties of the positive electron or “positron” find an easy interpretation if the theoretical scheme already exposed is accepted. When an electron and a positron\(^7\) come together, it can happen that they annihilate each other, neutralizing their opposite electrical charges and transforming their mass into radiant energy. In Dirac’s theory this phenomenon is interpreted as a transition in which the electron passes from the positive state in which it is initially found to the hole-state corresponding to the positron. In this way, the destruction of both corpuscles is evidently produced. To this, that we can call dematerialization process, a materialization process is opposed in which an electron passes from an occupied state of negative energy to one of the superior states, thus forming an ordinary electron and a positron that corresponds to the remaining gap in the negative state where the electron comes from. This materialization process with the creation of an electron-positron pair has been observed by irradiating substances of high atomic weight with very hard \(\gamma\) rays. In fact, the absorption of a \(\gamma\) quantum and the creation of an electron-positron pair with the described mechanism sometimes happen in the neighborhood of the nucleus. Turning now to the properties of the

\(^7\)Here the Spanish transcription says, wrongly, proton instead of positron (note of the editors).
nucleus, we will briefly expose some theoretical views on radioactive phenomena. These phenomena consist, as is well known, in the spontaneous disintegration of some nuclei, particularly heavy elements, which allow the emission of $\alpha$ or $\beta$ particles with high speed, with the subsequent transmutation into new nuclei. The emission of these particles is often accompanied by electromagnetic irradiation, i.e., $\gamma$ rays. As an $\alpha$ particle is nothing other than a nucleus of He (it has a charge +2), its expulsion determines a decrease of two units of the electrical charge of the nucleus that expels it; the residual element therefore comes to be placed two locations to the left of the original element on the periodic table of Mendeleieff. On the contrary, the expulsion of a $\beta$ particle (that is an electron and has electric charge -1) results in the displacement of a position forward, since it increases the nuclear charge by one unit. Applying the principles of wave mechanics to nuclear problems it has been fairly easy to construct a satisfactory theory for the ejection of $\alpha$ particles. In this theory, which is due to the Russian physicist Gamow, it is admitted that when an $\alpha$ particle is outside the nucleus, it is rejected by it in accordance with Coulomb’s law. On the other hand, it is hypothesized that the attractive forces necessary to justify the fact that the particle can be kept inside the nucleus for a long time act inside the nucleus. In other words, it is supposed that the force acting on the $\alpha$ particle depends on the distance $r$ from it to the center of the nucleus according to a law of the type represented graphically in Fig. 2, in which $\rho$ represents the radius of the nucleus. The potential energy has a value $W_0$ at a distance from the nucleus approximately equal to $\rho$. According to classical mechanics, an $\alpha$ particle initially located inside the nucleus, with an energy positive but smaller than $W_0$, could never leave it, not possessing enough energy to cross the barrier of high potential energy that surrounds the nucleus. According to wave mechanics it is found, on the contrary, that this impossibility of passage is not absolute and that instead there is a finite probability that the particle crosses the potential barrier leaving the nucleus. The probability of this process becomes smaller the higher and wider the barrier to cross.

The possibility of this passage is closely linked to the ondulatory nature of particles, postulated by wave mechanics and according to which even in the regions in which with classical mechanics the kinetic energy would be negative and in which therefore the particle could not penetrate, the tails of the wave representing the particle can enter, positioning the particle itself beyond the region forbidden according to ordinary mechanics.\[8\]

Based on these concepts, Gamow was able to provide a satisfactory interpretation of most of the phenomena related to the emission of $\alpha$ particles and in particular of the relationship that exists between the half-life and the energy with which the particles are emitted. His theory also gives a perfect account of the enormous variations in the magnitude of the half-life that, for various radioactive substances, ranges from fractions of a second to many millions of years. While the theory of the emission of $\alpha$ particles can currently be considered as quite satisfactory, the same cannot be said for the theory of the emission

\[8\]This is today known as “tunnel effect” (note of the editors).
of $\beta$ particles, and this for two reasons. First: we have seen the difficulties in admitting the existence of electrons inside the nucleus, so that it seems at first glance difficult to understand, furthermore, how they can get out. Second: while $\alpha$ particles, at least in typical cases, all leave the nucleus with the same energy, the $\beta$ particles leave the nucleus with a continuous distribution of energy; in other words, it is found that in the $\beta$ transitions the starting nucleus and the final product have both well defined energies, while the emitted $\beta$ particle can have different energies, which seems to be in conflict with the principle of energy conservation. And indeed, very authoritative physicists and among them Bohr (before all) have expressed the opinion that this may be a case in which the principle of conservation of energy is not fulfilled. Of course energy balance could be restored assuming to the existence of a new form of energy that escapes current observation methods. This should possess a very high penetrating power since it does not seem to be intercepted by the screens that are ordinarily used. A hypothesis of this kind has been supported by Pauli, who has thought about the possibility of a new elementary corpuscle of mass comparable to that of the electron and electrically neutral: this hypothetical corpuscle has been given the name of neutrino. The difficulty of conserving energy in the emission of $\beta$ rays would be eliminated, admitting that in a $\beta$ process an electron and a neutrino were emitted simultaneously between which the energy which is released in the process could be distributed in various ways, thus granting the possibility that electrons leave with different energies. On the other hand the neutrino, given its electrical neutrality and its tiny mass, could practically escape any current observation possibility. \footnote{Fermi’s theory of $\beta$ decay is currently accepted today. The neutron $n$ transforms into a proton $p$ through the process $n \rightarrow p e^- \bar{\nu}_e$, the negative electron $e^-$ being the $\beta$ ray, and $\bar{\nu}_e$ the (anti)neutrino (note of the editors).}

It remains to add a couple of words related to the other difficulty we had mentioned. Electrons leaving the nucleus would be interpreted in the most obvious way, assuming that
they were initially contained in it, but since we have seen that admitting this fact creates serious difficulties, another hypothesis can also be conjectured, and that is that the electron and possibly also the neutrino are believed to be the result of the transformation. This would imply a process in which a neutron transforms into a proton, thus obtaining an increase of one unit in the nuclear charge, while the formation of an electron occurs simultaneously in such a way that the conservation of the electrical charge is restored. Admitting the creation of another corpuscle is not an entirely new hypothesis, since there is already an example in radiation theory: when an excited atom passes into a lower energy state emitting radiation, a quantum of light, which can be considered created in the act of emission and not pre-existing inside the excited atom, leaves it.

One can thus try to construct a theory of $\beta$ rays analogous to the theory of irradiation of light quanta. Although such a theory is qualitatively possible according to experimental facts, it does not escape us the fact that it is going to be taken with great reserve at the moment, since in it the existence of the neutrino must be admitted, that is to say, of a particle whose existence is currently lacking any direct evidence.
Lecture V
The artificial disintegration of the nucleus

The topic that I want to address in this last lecture concerns what is possible to do artificially about the atomic nucleus. While it is relatively easy to produce modifications in the external electronic structure of the atom, altering the organization of the nucleus is a much more complicated problem for two reasons: first, because the nucleus is very small and therefore more difficult to reach with a bombardment, and second because the corpuscles of the nucleus are bound with much greater energies and therefore the projectiles must have a very high energy to be able to produce a break. The first projectiles that have demonstrated to be able to break the nucleus were the \( \alpha \) particles that are spontaneously produced by radioactive atoms. In this field, the first experience with positive success was carried out by Lord Rutherford in 1919; one of the best known cases of this process was the disintegration of nitrogen. The nitrogen nucleus has charge 7 and atomic weight 14, which is indicated with \( ^{14}\text{N} \). When the nucleus is hit by a \( \alpha \) particle, it absorbs it and immediately after emits a proton. The \( \alpha \) particle is a nucleus of helium of charge 2 and atomic weight 4 (\( ^{4}\text{He} \)); therefore, when it collides with a nucleus of nitrogen, a nucleus of charge 9 and of atomic weight 18 is formed by fusion. Then, this nucleus immediately emits a proton, i.e. a hydrogen nucleus (\( ^{1}\text{H} \)). The resulting nucleus then has charge 8 (it is therefore oxygen, O) and atomic weight 17, that is, \( ^{17}\text{O} \). The common O has atomic weight 18, but there is a rare isotope that has weight 17; the process is obviously a true transformation of elements in which N is transformed into O. This nuclear reaction has been particularly well studied, since one can observe in a Wilson chamber the path of the \( \alpha \) particle and that of the proton and of the nucleus of O, the latter acquiring a certain speed due to the shock it receives.

In the first disintegration experiences, the bombardment was obtained by means of \( \alpha \) particles, that is, by means of a natural projectile emitted by radioactive substances. In recent years, speeds comparable to those particles have been obtained on nuclei, and therefore it has also been possible to use other projectiles, protons in particular. The first experiences of this type were due to Cockcroft and Walton, who built a discharge tube in which hydrogen rays, which are protons, are launched through potential differences that reach almost a million volt. By launching these protons against the nucleus of some substances, particularly lithium (Li), it has been possible to observe the disintegration of this element. Lithium has two isotopes, one of atomic weight 6 and the other weighting 7; the one that suffers the interaction is the one of weight 7. When a proton strikes one such nucleus, it is incorporated by lithium, and an aggregate is formed that has mass 8 and charge 4, that is, twice as much mass and charge as the \( \alpha \) particle. This aggregate is unstable and immediately breaks.
down into two $\alpha$ particles according to the following nuclear reaction:

$$^{7}_3\text{Li} + ^1_1\text{H} \rightarrow ^2_4\text{He}$$

Here, too, the phenomenon can be followed in a Wilson chamber, where the track of the proton acting as a projectile and the two tracks of the $\alpha$ particles are observed, approximately in opposite directions.

Protons are in a sense more effective for producing nuclear decays than $\alpha$ particles, at least at the same energy. Indeed, the proton has charge 1, $\alpha$ particles have charge 2, and therefore when two projectiles approach a nucleus, the electrostatic repulsion is double on an $\alpha$ particle than on the proton. This reason, and another one which can be deduced from wave mechanics and depending on the fact that the proton has a smaller mass than the $\alpha$ particle, explain that, at least in the case of Li, which is one of the lightest elements, disintegration occurs even with relatively very small energies of the bombarding particle. Appreciable effects have been obtained even with protons artificially accelerated through potentials smaller than 20 000 volt. Neither with $\alpha$ particles nor with protons it has been possible to obtain effects larger than on light elements: the electrostatic repulsion is too strong and the particles fail to reach the core. This difficulty does not show up when the bombardment is carried out with neutrons, which do not undergo electrostatic repulsion and can therefore reach up the nuclei of the heaviest elements.

Until this year it was believed that the atom formed in these artificial decays was always necessarily a stable atom, until the discovery announced in January by the French physicists Joliot and his wife Irene Curie, daughter of the discoverer of radius, who indicated three cases in which the products obtained by bombardment with $\alpha$ particles are not stable, but subsequently disintegrate behaving like naturally radioactive bodies. In their experiences, these physicists used $\alpha$ particles, what a priori limits the possibility of producing an effect only to very light elements.

In the experiences we have carried out in Rome, we planned to use neutrons to carry out the bombardments. Neutrons, being as we said electrically neutral, can collide even with very heavy nuclei since they do not undergo electrical repulsion. I will briefly describe how the experience is carried out. For this experiment we need a neutron source, the substance to be bombarded, and an apparatus to reveal the possible artificial radioactivity produced by the substance.

The source is extremely simple. It is based on the fact that beryllium, under the action of the bombardment by $\alpha$ particles, spontaneously emits neutrons. Beryllium powder and a radium emitter are introduced into a glass tube that is then closed. The particles emitted by the radium emanation and by its decay products collide with the beryllium grains and activate the emission of neutrons. With the source that we were able to use, the number of neutrons fluctuated around one million per second; this is not a large number when compared to the number of particles leaving radium, in which a gram emits a few tens
of millions of particles per second. This lower intensity is compensated by the fact that neutrons are not rejected; when a neutron is directed exactly towards a nucleus it collides with it, while under the same conditions the probability that a $\alpha$ particle produces an effect is very small – it becomes practically negligible for heavy nuclei.

The apparatus for revealing a possible artificial radioactivity must be sensitive to the rays that come out of the possibly formed radioactive substance. The enormous sensitivity of the devices that can be built to reveal $\beta$ rays allows identifying the production of quantities of substances that would escape any other current method of observation. The apparatus for revealing the presence of electrons is a Geiger–Muller wire counter. It consists of a metallic tube at the ends of which it has two insulating covers between which a metallic wire, generally made of aluminum, extends along the axis of the cylinder. Between the tube and the wire a potential difference is established, regulated so that it is by little insufficient to produce the electric discharge; if an electron enters this environment, it produces a small ionization that is sufficient to cause a very short-term discharge, which is quickly extinguished. But in the time that this discharge lasts, it produces an alteration in the potential of the wire, which, suitably amplified, activates a counter that records the number of electrons that have entered the apparatus. Of course, in our case, the walls had to be thin enough for electrons to enter the apparatus; they were made of aluminum 0.1 to 0.2 mm thick.

In order to examine a substance, for example Fe, a cylinder of a suitable size is taken so that it can be lined up over the counter. First the source is placed on the cylinder and left for a certain time during which iron remains subject to the bombardment of the neutrons that come out of it; some of the nuclei reached by the neutrons are modified and become radioactive. After the neutron source is removed, these modified, radioactive, nuclei, gradually disintegrate, emitting an electron. If the Fe cylinder is now lined up over the counter, these electrons are registered by the counter and their number is recorded as a function of time. It is thus found that the frequency of disintegration decreases and reduces to one half of the initial one in a time characteristic of the bombarded element, which for example, in the case of iron, is equal to two and a half hours.

With this method we have tried to examine as many elements as possible, up to about sixty, and it has been found that a large number of them (about two thirds, that is to say about forty) produce radioactive effects. This large percentage of elements possibly subject to activation undoubtedly depends on the fact that neutrons are not rejected by the electric charge of the nucleus and therefore can act even on heavy elements. As confirmation of this, we have found that the percentage giving a positive effect is more or less the same for light as for heavy elements.

Now we are going to discuss the mechanism of the phenomenon and the experiences carried out to analyze it. Above all, it must be verified that the phenomenon, like all nuclear phenomena, is independent of the type of chemical bond. Thus, for example, Fe can be subjected to bombardment as an element or using its compounds, and the same phenomenon
is always found with the same intensity (naturally taking into account the different Fe content) and with the same period; the disintegration time is a characteristic constant of the bombarded element and it takes different values from element to element. The F activity is halved in 9 seconds, while for other elements the time is a few minutes, for others a few hours or a few days; the longest periods found so far correspond to Cl and S and are about 13 days.

The most probable scheme according to which decays occur is suggested by the already known cases of nuclear decay, in which we know that very often the bombarding particle is captured by the nucleus, which then emits a new particle. The three main schemes according to which the phenomenon occurs could therefore be the following:

1. Neutron absorption and emission of a $\alpha$ particle.
2. Neutron absorption only.
3. Other mechanisms (which cannot be excluded). For example, there may be cases in which the neutron is not absorbed or where other particles than those mentioned are emitted. If the nucleus absorbs a neutron and emits a $\alpha$ particle, its electric charge decreases by 2 units and therefore the radioactive nucleus formed is moved two places to the left with respect to the primitive element in the periodic table. If, on the contrary, a proton is emitted, a shift of only one position occurs, while in the third case the radioactive product formed turns out to be an isotope of the original element.

Even without making too special hypotheses about the mechanism of the phenomenon, it can be reasonably admitted that the radioactive element has an atomic number close to that of the bombarded element. In the case of Fe, for example, we can limit the investigation to the elements close to it in the periodic system, that is, to Cr, Mn, Fe, Co and Ni. In order to decide between these possibilities, a chemical analysis of the formed element cannot be carried out directly because the difference is so small that it cannot be evidenced with any of the ordinary methods of chemical analysis, being necessary to add a radioactively inert isotope to the radioactive element possibly formed, which serves to drag it. A certain amount of metal is subjected to neutron bombardment and then dissolved in nitric acid; small amounts (a few milligrams) of the salts of all the suspected elements (Cr, Mn, Co, Ni) are added to the nitrate solution; with the standard methods of chemical analysis these elements are separated again from each other and from Fe, and the five fractions are successively placed next to the counter to know which of them is radioactive. In this case, for example, it was found that the activity continues in the Mn, indicating that Fe has been transformed into a radioactive isotope of Mn, from which it would appear that in this case the radioactive product has an atomic number one unit lower than the original element and therefore a proton has been emitted. In other cases, it has been found that
the atomic number decreases by two units, which would indicate emission of a $\alpha$ particle. There have been cases, finally, in which the radioactive element is an isotope of the bombarded element, which could be interpreted admitting that the neutron has simply been absorbed without subsequent emission of charged particles. The difficulty of performing a chemical analysis of the type described is in many cases due to the short time available to do it, which is sometimes 2 to 3 minutes. For this reason, chemical analysis of active products have been carried out in about fifteen cases and it is sometimes found that the same radioactive element can be formed in different ways. For example, radioactive Mn that is formed by bombarding Fe with a two and a half hour period is also obtained bombarding Co and Mn; analogously an isotope of V is formed, having a period of about 4 minutes, when bombarding V, Cr or Mn.

Finally, I will talk about the activation of uranium (U), the heaviest of the known elements. The investigation is complicated in this case by the fact that U is spontaneously radioactive and its natural radioactivity would mask any further effects due to neutrons. To carry out the experience, you can take advantage of the fact that the U only emits $\alpha$ particles, which are not registered by the counter because they have insufficient penetrating power to cross it. But since U is always mixed with its decay products, some of which emit $\beta$ particles, chemical operations are necessary to eliminate them. After purification, for at least a certain time, no spontaneous emission of $\beta$ particles occurs, and the activity regenerates slowly as the separate decay products are formed again. After this preliminary treatment, the U subjected to neutron bombardment shows a relatively intense activity with a period very different from those corresponding to natural radioactive bodies. The phenomenon is rather complicated, because the decrease in the activity produced by the neutrons is not simply exponential, but is carried out by superimposing several exponentials with different periods, finding at least 4 periods (10 seconds, 40 seconds, 13 minutes and 100 minutes), and possibly some longer. This indicates a greater complexity of the phenomenon, probably due to the fact that some successive transformations take place. Also in the case of U it is interesting to chemically investigate the nature of the active elements formed. We have especially devoted ourselves to the 13-minute period element which is the most convenient for investigation and we have tried to establish whether this was an isotope of the U itself or of any of the preceding elements ($^{91}$Pa, $^{90}$Th, $^{89}$Ac, $^{88}$Rd). Here, too, it is necessary to proceed in a slightly different way from that described for the common elements, because many of the elements with an atomic weight close to that of U are very rare and the quantities available are not high, but can be developed by radioactivity techniques. To investigate whether the element living 13 minutes is an isotope of one of these substances, the two materials are mixed and it is then searched for chemical reactions capable of separating them at least in part. The existence of such a reaction should be considered as proof that the two elements are not isotopes. The experiences carried out in this investigation seem to indicate that the element produced is not an isotope of U, nor of the elements that precede it in at least ten squares of the periodic system; it has therefore been
thought that it could have an atomic number greater than 92, in which case the production of an element that does not exist in nature would be produced due to the effect of neutron bombardment and that after an ephemeral life of few minutes would again be destroyed. It is natural that before these results can be confirmed it will be necessary to carry out a series of control tests and to fully examine the table of the chemical properties of the new element.

Finally I add that, according to journalistic news, it seems that these days a bohemian scientist has come to find an element that he suspects has atomic number 93 in the pitchblende from which the U is extracted. If this news were confirmed it would lead to a new possibility of obtaining element 93, perhaps in an isotope form of that obtained with neutron bombardment.
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