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Epistemology of Research on Radiation and Matter: a Structural View

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Abstract The modern understanding of radiation got its start in 1895 with X-rays discovered by Wilhelm Röntgen, followed in 1896 by Henri Becquerel's discovery of radioactivity. The development of the study of radiation opened a vast field of research concerning various disciplines: chemistry, physics, biology, geology, sociology, ethics, etc. Additionally, new branches of knowledge were created, such as atomic and nuclear physics that enabled an in-depth knowledge of the matter. Moreover, during the historical evolution of this body of knowledge a wide variety of new technologies was emerging. This article seeks to analyze the characteristics of experimental research in radioactivity and microphysics, in particular the relationship experience-theory. It will also be emphasized that for more than two decades, since the discovery of radioactivity, experiments took place without the theory being able to follow experimental dynamics. Some aspects identified as structural features of scientific research in the area of radiation and matter will be addressed through historical examples. The inventiveness of experiments in parallel with the emergence of quantum mechanics, the formation of teams and their relationship with technology developed from the experiments, as well as the evolution of microphysics in the sense of "Big Science" will be the main structural characteristics here focused. The case study of research in radioactivity in Portugal that assumes a certain importance and has structural characteristics similar to those of Europe will be presented.

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1. Introduction

The modern understanding of radiation began in 1895, with the discovery of X-rays produced in gas discharges.[1] Another type of ionizing radiation was discovered in the following year, this time not produced in discharges but spontaneously emitted by uranium salts. The spontaneous emission of radiation by matter was called “radioactivity”, a designation that now has a much greater scope than at the time of its discovery. In fact, this phenomenon of emission of radiation, not exclusive of uranium compounds, as verified later, was the source of research that led to the emergence of new fields of knowledge such as atomic and nuclear physics, particle physics, as well as to numerous applications, from biology to astrophysics. It is in this broad sense that we refer here to research in “radioactivity”: a set of investigations and discoveries that began with the discovery of the new radiations and led to a new physics and a new theory of matter.

This paper offers a structural epistemological analysis of the development of knowledge in the area of radioactivity, in order to detect patterns in the theory-experiment interaction. A discussion, in particular, of the existence of an “experiment-theory hierarchy” will be undertaken.[2] This type of analysis has forcibly to refer to the most important experimental and theoretical achievements in radioactivity and nuclear physics, which will be done in the next three sections. In this analysis about half a century of history will be traversed, with the purpose of identifying the evolutionary lines and the idiosyncrasies of the research on radioactivity.

The discovery of X-rays and radioactivity in the late 19th century would be followed by other experiments of increasing complexity that lasted for several decades before the theory could explain the origin of such radiations. By their place in the emergence and initial development of the area of radioactivity, the experimental results will be especially focused here. However, some essential theoretical developments such as the emergence of quantum mechanics will be accounted in this text, but only briefly.

1 Maia et al., 2010.

2 Franklin, 1986.

A long-standing debate in the epistemology of experimental sciences refers to the relative roles of theory and experimentation. Philosophers of science have emphasized the essential role of experiments in the testing of theories,[3] but they also play other important roles.[4] They are, for example, essential in exploring new phenomenological realms and discovering new effects and phenomena. Nevertheless, experiments are still an underrepresented topic in main stream philosophy of science.[5] In the case of microphysics, the experimental study of radiation led to unexpected discoveries about the structure of matter, a fact that will be emphasized.

The historical facts cited were chosen so that they may allow such an analysis but they do not represent a global history of radioactivity that has already been elaborated by several authors as for example the physicist Emilio Segrè[6] who knew in detail the events.

After the critical account of events and discoveries, the existence of a well-defined structure in the research in radioactivity and nuclear physics will be proposed in section 5. The sequence of historical facts described will then be used to highlight some epistemological characteristics of experimental research in radioactivity, such as inventiveness, the role of instrumentation and the formation of teams. A case study will be also presented in section 5.

In the concluding remarks, a synthetic presentation of the characteristics of radioactivity that have been collected throughout the text will be made.

2. Radioactivity: from the Discovery to the Achievement of Nuclear Reactions

The study of the phenomena of luminosity in the discharges in gases led, in the late 19th century, to the important discoveries of cathode rays in 1869 by Johann Hittorf (1824–1914) and of X-rays in December 1895 by Wilhelm Röntgen (1845–1923). In 1897 J.J.Thomson (1856–1940) showed

3 Franklin, 2007.

4 Franklin and Perovic, 2016

5 Pickering, 1992.

6 Segrè, 1980.

that cathode rays were composed of negatively charged particles, later named electrons.

X-rays represented, in their time, a truly sensational discovery, with a greater social impact than others discoveries also very relevant from the point of view of research in physics. In 1896 alone, as many as 50 books and 1044 articles[7] about the new rays were published, with a journal such as Science dedicating a total of 23 articles to it. Besides that, newspapers and popular magazines also published and commented the discovery. But in addition to this great interest in X-rays the discovery also motivated studies of radiation that led to the discovery of radioactivity.

After a session in the French Academy of Sciences on 20th January 1896 in which Poincaré presented the paper and photos sent to him by Röntgen, Henri Becquerel (1852–1908) decided to investigate the possible relation between the fluorescence presented by the glass of the discharge tube and the fluorescence of uranium that he already knew of. In 1896, in the course of his experiments, he concluded that uranium emits radiation spontaneously: radioactivity had been discovered.

The term radioactivity was coined later by Maria Sklodowska Curie (1867–1934). She began investigating the phenomenon recently discovered by Becquerel, analyzing different compounds of uranium and of thorium, also radioactive, and confirmed that the activity depends on the amount of element present and not on its chemical form. She also analyzed some natural ores containing uranium and thorium and discovered that they were more active than the amount of these elements contained in the ores could justify. Together with her husband Pierre Curie (1859–1906) they extracted uranium from a uranium ore – pitchblende - and concluded that it contained other unknown radioactive elements which they named polonium and radium. For this work, in 1903, they were awarded, together with Becquerel, the Nobel Prize in Physics. Radioactivity was becoming an interesting subject.

Ernst Rutherford (1871–1937) was one of the physicists fascinated by the study of radioactivity and who would come to play a pivotal role in the field. He achieved important results from the experiments he carried

7 Glasser, 1933.

out or coordinated. But despite being mainly an experimental physicist he obtained the first theoretical result of great importance in radioactivity: the interpretation of the phenomenon of spontaneous emission of radiation, a question until then unanswered. Spontaneous radiation was explained by Rutherford as a result of transformations of the atoms or, what may be called, "transmutation of the elements". It is now known that radioactivity results from the transformation of atomic nuclei, but in 1902 this interpretation was not possible because it was not yet known that the atom has a structure. The atoms (or atomic nuclei) of some elements emit radiation because they are unstable and when transforming into other elements they emit one or more kinds of radiation. Rutherford needed some boldness to present an interpretation that was based on transformation of the chemical elements (transmutation), an idea with roots in alchemy. However, his idea resulted not from simple speculation but from the results of a series of chemical experiments that he and Frederick Soddy (1877–1956) conducted in collaboration.[8]

It should be stressed that this fundamental idea for microphysics is, in fact, the result of some experiments without any intervention of an independent theoretical study. In microphysics there are other examples of the same type in which important theoretical conclusions arise from experiments. This may be considered to be one of the standards of the epistemology of radioactivity: the inventiveness of experimental processes. Rutherford's work is precisely a prime example of the inventiveness of experimental work in radioactivity.

In 1908, for his result and his methods, Rutherford was awarded the Nobel Prize in Chemistry, even though he was a physicist. Actually, however, it can be said that physics and chemistry have crossed their activities since the beginning of radioactivity, a field that has progressively become multidisciplinary by its integration in the work of other scientific areas such as geology, biology and medicine.[9]

8 Rutherford and Soddy, 1902.

9 Multidisciplinarity is in fact one of the relevant characteristics of radioactivity that indeed will be referred in this text.

Later, Rutherford devised some experiments, the called “gold leaf experiments”,[10] in which a thin gold leaf is “bombarded” with alfa particles emitted by a radioactive element, performed between 1908 and 1913 by his assistants Geiger and Marsden, allowed Rutherford to propose his nuclear model of the atom.[11] This kind of bombardment experiment, born in Rutherford’s laboratory, is important not only because it led to Rutherford’s atomic model but also because the experimental process proved to be fruitful. In fact, generally speaking, this was the process used later in a much more sophisticated way in particle accelerators to penetrate the atoms and nuclei and allow getting insights about their structures.

From 1917, other experiments were made by Rutherford: the first artificial nuclear transmutations of one element into another. Using alpha radiation, he converted nitrogen into oxygen through a nuclear reaction.[12] This was the first observation of an induced nuclear reaction, that is, a reaction in which the particles originated by the decay of an atomic nucleus are used to transform it in another atomic nucleus.

The first artificial nuclear transmutation achieved by Rutherford, besides providing a powerful new instrument in future experiences, opened new perspectives from the point of view of knowledge of matter.[13] First, nuclear reactions experiments led him to theorize about the existence of neutrons, an idea that was confirmed in 1932 by the experiments carried out by another of his collaborators, James Chadwick (1891–1974). Chadwick, who recognized neutrons that had earlier been produced but not identified by other scientists and later by himself,[14] was awarded in 1935 the Nobel Prize in Physics.

But beyond this first result, nuclear reactions have revealed enormous potentialities over the years, from Rutherford to the present day, particularly in the study of the atomic nuclei.[15] Produced in accelerators or in nature, nuclear reactions and their interpretation are the main activity

10 Rutherford, 1911.

11 Rutherford, 1914.

12 Rutherford, 1919.

13 Stuewer, 1986.

14 Chadwick, 1932.

15 Basdevant et al., 2005.

of most nuclear scientists nowadays and allow, for example, to explain many astrophysics phenomena, as the energy production in the stars,[16] and the interaction of cosmic rays with matter.[17]

Summing up, the previous paragraphs lead us to conclude that Rutherford's experimental work allowed him to obtain, between 1902 and 1919, several important results: the interpretation of the phenomenon of radioactivity, the establishment of an atomic model and the accomplishment of an artificial transmutation obtained through a nuclear reaction.

All these Rutherford's results were important but especially the latter represents a fundamental change in the way to investigate in microphysics. Indeed, in seeking to establish an epistemology of radioactivity it is essential to emphasize the role played by nuclear reactions in the development of the study of matter. These reactions are relevant not only for themselves and for being at the origin of several discoveries but also because they represent a fundamental step in microphysics: the imitation of natural processes through scientific experiments. This stage was also determinant in the evolution of other sciences, such as the electromagnetism experiments of the 19th century allowing the production and control of electrical and magnetic phenomena[18] known since antiquity.[19] The simulation of a natural phenomenon in the laboratory also provides conditions for the establishment of cause-effect relationships. Current examples of these possibilities are some microbiology results as the genetic mutations achieved in the laboratory.[20,21]

Any scientist knows that in order to progress in knowledge it is not enough to observe nature, it is necessary to interact with it. Getting to reproduce in the laboratory part of the natural processes is a very effective way to study them. What would chemistry be without synthesis[22]? What

16 Bethe, 1939.

17 Rossi, 1964.

18 Darrigol, 2000.

19 Lindell, 2009.

20 Muller, 1927.

21 Woods, 2012, 35–37.

22 Nicolaou, 2014.

would be the research in biology and medicine without the possibility of reproducing in the laboratory the chemistry of life?[23]

There is much prior knowledge required to recreate natural processes in the laboratory. However, the results obtained from these experiments can be fundamental in the evolution of a science. In microphysics, Rutherford's experiment proved to be an extremely powerful means of investigating the nature of matter that continued to be developed by Rutherford's collaborators in the Cavendish laboratories in Cambridge and also in several other laboratories in Europe and the United States. In 1932, John Cockcroft (1897–1967) and Ernest Walton (1903–1995), who had been students of Rutherford, conceived and built, in Cambridge, one of the first particle accelerators.[24] These devices allow to accelerate atomic particles and then using them to bombard nuclei in order to provoke different types of nuclear reactions such as transmutations or disintegrations.

Cockroft and Walton bombarded lithium atoms with protons accelerated to high velocities by a strong electric field causing for the first time in the history of microphysics, the division of atomic nuclei, a feat popularly known as splitting the atom. In this nuclear reaction the mass of the proton and lithium was converted into the mass of two alpha-particles and kinetic energy. This first artificial disintegration of an atomic nucleus gave them the Nobel Prize in Physics in 1951.

3. Towards "Big Science": Accelerators and Nuclear Reactors

The first nuclear reactions performed made evident their importance in the study of matter. It was also realized that it was indispensable to accelerate particles in order to provoke interesting nuclear reactions. Thus, from the 1920s onwards several types of accelerators for physics research were designed and built in the United States and Europe. Accelerators have then become one of the most important instruments of fundamental and applied research, for example in the study of materials and in astrophysics.

23 Rose, 1991.

24 Kleppner, and Kolenkow, 1973.

Since 1930 the size, power and possibilities of the accelerators have not stopped growing. The dimensions and complexity of such an instrument, in terms of both its design and technology, summons the work of numerous scientific and technological disciplines. Its use obligates any physics experiment to become an agreement between specialists rather than an individual investigation, as it did in radioactivity until the 1930s. This situation, which also exists in other areas, characterizes the so-called "Big Science" a term used for the first time by Alvin M. Weinberg, director of Oak Ridge National Laboratory, in a paper published in Science in 1961.[25]

This way of doing science has become prevalent or even exclusive in nuclear physics today. Nuclear reactors are, along with accelerators, the large "tools" that have resulted from fundamental research. The basic physical process that takes place in a nuclear reactor is the fission of a heavy radioactive nucleus, for example uranium. The phenomenon of nuclear fission that was discovered by Otto Hahn's team. In 1938 the radiochemists Otto Hahn (1879–1968), Lise Meitner (1878–1968) and Fritz Strassmann (1902–1980), while bombarding elements with neutrons in their Berlin laboratory, found that during neutron bombardment, uranium nuclei changed greatly and broke into two roughly equal pieces. The uranium nuclei split originating radioactive isotopes with atomic masses about one half of the uranium atomic mass, such as barium, krypton, and strontium, and release also some neutrons.[26] In this process, called nuclear fission, energy is released. If a chain reaction occurs, i.e. if the neutrons that result from the first fission cause new divisions and the process goes on, energy released can be huge. In the atomic bomb, as in nuclear power plants, this process of nuclear fission is used to obtain energy, but in the case of power plants the reaction is controlled so as not to become explosive.

Although the purpose of this article is not to address the ethical questions of science, when analyzing the history of radioactivity and nuclear physics it is impossible not to mention the social reactions to nuclear

25 Weinberg, 1961.

26 Anderson et al., 1939.

bombs[27] but also to nuclear power plants[28] over which there is a large controversy documented by wide bibliography.[29]

The evolution of radioactivity research towards an increasing in the scale and complexity of experiments has made evident the role of technology in scientific development.[30] But throughout the history of science other examples have shown that experiments demanded not only good ideas but also some technical achievements,[31] a fact that is notorious mainly from the 19th century.[32] A paradigmatic example of the importance of technological improvements in scientific research in microphysics is that of the vacuum pump invented by in 1650 by Otto von Guericke (1602–1686) but whose origins and applications go back to Greek civilization[33] . The improvement of vacuum pumps would prove to be fundamental in the physics experiments of the 19th and 20th centuries. Actually, the achievement of better vacuum values obtained by researchers who worked with cathode ray tubes in the 19th century allowed obtaining fundamental results for the emergence of microphysics.[34]

Technical innovations also have proved essential for example in the development of science in the case of lenses and telescopes in the Renaissance.[35] There are many other well-known examples, such as the microscope whose technical improvements[36] have revealed new worlds,[37] as well as the spectroscope which may be credited for decisive progress, particularly in chemistry and atomic physics.[38] Most inventions of apparatus and measurement techniques are closely linked to scientific research and sometimes constitute giant steps in the search for knowledge of phenom-

27 Beatrice Fihn and Thurlow, 2017.

28 OTA, 1984.

29 Greenpeace, 2018.

30 McMillan, 1969

31 Singer, 1941.

32 Bernal, 1953.

33 Hill, 1996, 140–150.

34 Serra et al., 2009.

35 King, 2011.

36 APS News, 2004.

37 *Nature Cell Biology* , Editorial, 2009.

38 Peres, 2005

ena. Precisely in the study of radiation, the invention of new experimental methods and the development of technologies was a constant in research for some forty years, from the discovery of X-rays to the development of particle accelerators in the 1930s.

For some centuries research work was developed in an almost individual way but in many areas of knowledge this situation changed radically around the second half of the 19th century: great laboratories were founded such as the one directed by Adolphe Wurtz (1817–1884) in France[39] as well as the laboratory directed by Kamerlingh Onnes (1853–1926) in the Netherlands[40] and the Kaiser Wilhelm Institute for Chemistry in Berlin. After World War II, technological requirements of the most important nuclear physics experiments grew exponentially throughout the twentieth century. The most famous example of the dimension reached by nuclear physics experiments is CERN.[41]

The formation of teams, together with technological innovations, became central for the development of scientific work. This was also the case for radioactivity and nuclear physics. Furthermore, it may be said that in the 20th century there are some laboratories where the team dynamics is more important than its size in what concerns the development of the research work. In nuclear physics, the Rutherford teams in Manchester and Cambridge, as well as the Fermi groups in Italy and later in the United States are examples of successful research work coordinated by leaders who manage to bring together quality scientists around them. Of course, other important discoveries have been made in Europe and the United States by other teams. The Curie laboratory stood out for the discovery of new radioactive elements, soon after the discovery of the radioactivity and later, in 1934, for the discovery of artificial radioactivity by Irène Curie (1897–1956) and Fredéric Jolliot (1900–1958). The *Institut du Radium* founded in 1909 by Marie Curie later became the *Institut Curie,* one of the leading medical, biological and biophysical research centers in the world.

39 Rocke, 2001.

40 Blundell, 2009.

41 CERN (Conseil Européen pour la Recherche Nucléaire) is the European Organization for Nuclear Research that operates the largest particle physics laboratory in the world. Established in 1954, the organization is based in a suburb of Geneva on the Franco-Swiss border.

One relevant aspect of radioactivity research that we have not yet mentioned, despite its extraordinary importance in the knowledge of radiation, was the development of radiation detection systems. Its history, parallel to that of radioactivity itself, is of particular interest because it helps to clarify how radioactive research worked in its early stages. While not mentioning the details of the detection systems, nor its late development, we would like to make reference to the invention of some of the detectors that involved fundamental physics studies.

The first one cannot but be the electrometer constructed by Pierre Curie and his brother Jacques Curie based on the piezoelectric effect they had investigated[42] even before the discovery of radioactivity. Another researcher, William Crookes (1832–1919) an English chemist and physicist pioneer of vacuum tubes invented the spinthariscope in 1903.[43] In 1908 Rutherford and Hans Geiger (1882–1945) described the first cylindrical electrical counter for alpha particles,[44] the first model of Geiger-Muller counter, an instrument made famous by its presence in the war and spy movies, as well as for its use in field detection of uranium ores.

The Wilson Chamber was invented in 1911 by Charles Wilson (1869–1959) when studying cloud formation and optical phenomena in moist air. The invention of the chamber and the explanation of its functioning were reported by Wilson himself when he won the Nobel Prize in 1927.[45]

Although the invention of these instruments is due largely to the researchers on radiation phenomena, its improvement has been achieved in the following decades by technicians of various disciplinary areas, particularly electronics and computing. In fact, detection systems were perfected by the development of equipment to receive signals from radiation detectors, process them and produce a convenient output.[46]

42 Molinié & Boudia, 2004.

43 Spinthariscope was a sort of microscope invented by William Crookes in which an observer could count the scintillations produced by particles emitted by radioactive substances on a screen of zinc sulfide (Frame, //www.orau.org/ptp/articlesstories/spinstory.htm.)

44 Rutherford & Geiger, 1908.

45 Wilson, 1927.

46 Flakus, 1981.

4. Experiments, Theory, and the Nature of Matter (1911–1936)

It has already been pointed out that the first ideas about the origin of radiation phenomena arising from either discharge in gases or radioactive substances are due to experimental physicists, J.J. Thomson and E. Rutherford. Although these ideas had been just starting points for building a theory about the nature of matter, its impact was enough to stimulate new experiences and theoretical hypotheses. The previous sections reported several experiments whose results were essential for the construction of ideas about atomic and nuclear structure of matter. The knowledge of the microscopic constitution of matter occupied experimental and theoretical physicists and chemists, and became the main purpose of the so-called microphysics until the World War II.[47] Meanwhile, the situation of microphysics has evolved enormously giving rise to the physics of the particles and to other areas of knowledge such as atomic and nuclear physics and chemistry, molecular physics, plasma physics, quantum optics, etc. But particle physics is often considered to be the "heir" of microphysics born in 19th century physics laboratories, since its purpose is to understand the "ultimate nature of matter”.[48]

To fulfill this purpose the experimental results obtained up to 1920 were essential, but it can be said that after 1920s to the present-day theory and experimentation succeed each other in obtaining results and interpretations concerning the structure of matter. Experiments are difficult to perform and interpret, and theories are difficult to formalize and verify. In trying to overcome these difficulties it was then established a tangle of interactions between theory and experience, a situation that is typical in the modern study of the matter and that can be considered one of the characteristics of the progress of knowledge in the field.

This intricate experiment-theory story begins undoubtedly with the interaction between two major figures in experimental and theoretical research: Ernst Rutherford, and Niels Bohr (1885–1962), whose “means of communication, with their differences, remains a mystery”.[49] In fact,

47 Galison, 1997.

48 Davies, 1992.

49 Segrè, 1980,113.

"Rutherford's attitude toward theoretical physics was peculiar. He was certainly not a theoretician himself and was quick to make fun of theory and theoreticians".[50] For those who have personally met these two great personalities of science, Rutherford, and Bohr, it is difficult to understand how their collaboration was possible. Emilio Segré (1905–1989), an Italian-American nuclear physicist, Nobel laureate, but also a great storyteller, along thirty pages of his book,[51] unravels that "mystery".

Niels Bohr had obtained his PhD in 1911 with a thesis on electron theory, but despite being a theoretical physicist, he conducted his post-doctoral work between 1911 and 1912 in Rutherford's laboratory in Manchester directly participating in the experiments.[52] As referred in section 2, after his gold leaf experiments, in 1911, Rutherford had proposed the nuclear model of atom. "Bohr took this model very seriously in spite of its mechanical and electrical instability",[53] a difficulty already pointed out by Rutherford himself. From the Rutherford model, Bohr constructed his model integrating several theoretical and experimental results, Bohr constructed his model integrating several theoretical and experimental results such as the "quantization"[54] of Max Planck (1858–1947) and Albert Einstein (1879–1955) and the study on the atomic dimensions carried out by Arthur Haas (1884–1941). In the beginning of 1913, in order to construct his model, and at the suggestion of a student, Hans Hansen, Bohr also considered other data: the distribution of spectral lines obtained by Johan Balmer (1825–1898) in 1885 from an empirical formula elaborated from experimental results.[55] We cannot fail to observe that Niels Bohr's ability to integrate various data and knowledge was very important for the progress of knowledge in microphysics.

Bohr's most significant contribution was proposing a model for the hydrogen atom using the quantization of energy, which could better account for experimental data and theoretical objections. He considered

50 Segrè, 1980, 113.
51 Segrè. 1980, 101–131.
52 Kennedy, 1985, 3–15.
53 Segrè, 1980, p. 121.
54 Bohr, 1913.
55 Segrè, 1980, 121–127

that electrons moved around the nucleus in fixed circular orbits corresponding to given values of energy which are directly related to the emission lines in the hydrogen spectrum.

Spectra are images that show the intensity of light being emitted over a range of energies that appears in a series of lines. The spectrum is called an atomic spectrum when it originates from an atom in elemental form. Atoms and molecules have different spectra which can be used to detect, identify and quantify information about each atom or molecule. Although the history of spectroscopy had begun in the 17th century, and it had much progressed until the 19th century, it had not yet been possible to explain why an atom emits radiation with particular wavelengths. That is, it was a mystery why the spectrum of an element was composed of separate lines and why different elements had different lines or, in other words, why there is a "quantization" of spectra. Prior to Bohr's model of the hydrogen atom, scientists were unclear of the reason behind the quantization of atomic emission spectra. Precisely, the quantization of the electronic orbits proposed by Bohr provides an explanation for the quantization of the spectral lines.

Bohr's ideas and formulae had a controversial reception but were eventually accepted after World War I. The Bohr model was later used in the interpretation of experiments and in theoretical developments, having suffered successive reformulations. One such reformulation was to generalize the Bohr model to atoms other than the hydrogen atom. An important modification was carried out by Arnold Sommerfeld (1868–1951): using new experimental data he quantized the angular momentum introducing in the model the possibility of elliptic orbits what correctly explained the so called Zeemann effect,[56] discovered in 1896.

Pieter Zeemann (1865–1943) observed that, when light was in the presence of magnetic fields, individual lines in the electromagnetic spectrum were split into many lines. Hendrik Lorentz (1853–1928) explained this effect by the interaction between the electrons of the atom and the magnetic field. In 1902, together with Zeemann, he received the Nobel Prize for Physics for the discovery and explanation of the Zeemann effect.

56 Arabatzis, 1992.

According to Arabatzis,[57] the Zeeman effect "had a life of its own which cannot be adequately understood as an offspring of pre-established theoretical anticipations". Moreover, Zeeman effect is a nice "example of how experimental phenomena persist even while theories about them undergo revolutions".[58]

Only the formulation of quantum mechanics, from 1925, allowed integrating the Bohr atomic model into a physical theory. However, it can be said that the history of quantum mechanics begins early in the 19th century with experimental discoveries and theoretical hypotheses: the discovery of the cathode rays by Faraday (1838) of the photoelectric effect by Hertz (1887), the problem of the blackbody formulated by Kirchhoff (1860), Boltzmann's idea that the energy states of a physical system are discontinuous or discrete (1877) and finally Planck's quantum hypothesis that the radiation energy exists in the form of elements or quanta (1900).

The theoretical framework in which the experimental results of microphysics were being justified had a considerable development during the first decades of the 20th century, not only in the field of radioactivity studies. A collection of results was obtained by Max Planck, Albert Einstein, Peter Debye, Satyendra Bose, Hendrik Kramers and other who contributed to what can be named "old quantum theory"[59] that predate modern quantum mechanics. These results were never complete or self-consistent, but consisted of a set of heuristic prescriptions which are now understood to be the first quantum corrections to classical mechanics.

The most important conceptual contribution to reformulating the Bohr model came from the invention of quantum mechanics, which led to a great transformation of atomic physics. A major problem with Bohr's model was that it treated electrons as particles that existed in precisely-defined orbits. In 1925 Werner Heisenberg proposed a formulation of quantum mechanics, in which Bohr's model of electrons traveling in quantized orbits was extended into a more accurate model.[60]

57 Arabatzis, 1992, 386.

58 Hacking, 1984, 172 (cited in Arabatzis, 1992, 386)

59 T*er Haar, 1967.*

60 Pleijel, 1932.

It is reasonable to think that the history that begins with the discovery of radiations would not be complete without a few more words about quantum mechanics that in a way represents an epilogue to the studies that began in the laboratories of Marie Curie, Ernest Rutherford and many others. After Heisenberg, Erwin *Schrödinger* (1887–1961) and Louis *de Broglie* (1892–1987) presented other formulations of quantum mechanics[61] and soon in the following years new ideas and theoretical predictions came to be confirmed, as for example the wave of matter[62] and the existence of a new particle, the positron.[63] During the decades that followed his invention, quantum mechanics became a thriving area, extending its scope and applications.[64] With the development of quantum mechanics, for the first time in microphysics the theory assumes a primordial role, that of explaining and predicting the behavior of matter at the microscopic level. Experimental practice becomes primarily a confirmation or an application of theory which means that there has been a reversal of roles in microphysics. However, experimental studies have continued to play a key role, for example in research with accelerators or nuclear reactors.

5. Looking for the Main Characteristics of Radioactivity Research

When studying the history of radioactivity since its discovery, it can been noticed that during the first decades of research into radioactivity experiments have always been ahead of a fundamental theory in physics describing the nature and structure of atoms.[65] The traditional philosophy of science implicitly considers theory more important than experimental practice that is relegated to a role of confirmation (or refutation) of theory and search of its possible applications.[66] However, in the last decades

61 Doyle, 2018.
62 De Broglie, 1970.
63 Dirac, 1928
64 Zettili, 2009.
65 Feynman et al., 1964.
66 Soler et al., 2014.

some philosophers[67,68,69] started stressing the importance of experimentation by itself, pointing out its relevance in the evolution of knowledge and in some cases, even in the establishment of new fields of research.[70]

The history of microphysics drawn here seems to confirm the ideas of Hacking and other philosophers associated with the “new experimentalism”. In fact, this scientific domain has evolved for about thirty years mainly at the expense of new experiments and new experimental techniques. In research, from Becquerel’s discovery in 1896 until the acceptance of Heisenberg’s and Schrodinger’s theory of quantum mechanics in the 1930s, the prevalence of experimentation can undeniably be recognized through discoveries and progress in knowledge, evidence that can be easily verified through the timeline of findings, published, for example, by Atomic Heritage Foundation.

In the previous sections some of the most relevant results have been mentioned, in order to point out the inventiveness of experimental research, an essential characteristic of the radioactivity. Many of the interpretations of phenomena are due to experimenters who built images of the atom, of the nucleus and of the phenomena occurring in the laboratory, such as nuclear reactions or nuclear fission. In addition, it should be noted that some important theoretical results of the early twentieth century, such as Planck’s (1900) and Einstein’s (1905) hypothesis that energy is composed of ‘quanta’, only gain relevance with the atom model of Bohr-Rutherford which was born from an experiment.

In reporting the first decades of the history of radioactivity, several examples were given of how experimenters, in addition to planning and performing experiments, also interpreted them, proposing explanations for phenomena occurring in the laboratory. But beyond achievements such as the interpretation of nuclear reactions and fission, the experimental work in radioactivity was in the origin of the first modern atomic model. Only then theoretical physicists seemed to take into account what had been happening in the radioactivity labs about twenty years ago. In

67 Franklin, 1986.

68 Hacking, 1983.

69 Radder, 2009.

70 Franklin and Perovic, 2016.

other words, until 1925 theoretical research in microphysics seemed to go on his own way without interfering with the experiments. The big exception was the theoretical physicist Niels Bohr who worked for some years with Rutherford thus taking forward the theoretical study of the atom. After Bohr and up to today the interactions between experimenters and theorists have been valued. However, sometimes the dialogue between them remained difficult[71] especially in cases where the relation between experimental results and theory was unclear.[72] But with the development of quantum mechanics, it seems that, finally, theoreticians and experimenters have begun to study the same thing although using different means.

Another relevant aspect in the development of radioactivity was the role of instrumentation.[73] Although not having the same media prestige as the telescope or the microscope, some of the instruments of microphysics have also completely transformed the possibilities of research and discovery, such as the Wilson chamber or the Geiger-Muller detector. The investigation in microphysics was the origin not only of instruments of measurement, but also of machines where the matter is transformed to be better studied, as it is the case of accelerators and nuclear reactors.

Large instruments were part of microphysics since its inception through cathode ray tubes and other discharge tubes. Moreover, it can even be said that microphysics was literally born in these machines because it was in them that the X-rays were “seen” for the first time. The discharge tubes which in the nineteenth century were essentially used for scientific research ended up having numerous applications, a fact which could serve as the starting point for an inquiry into the purposes and applications of instruments designed and manufactured for scientific research.[74] In any case in microphysics there are several examples that from this point of view deserve a more in-depth analysis that cannot be done here.

71 Lenoir, 1988.

72 Franklin and Perovic, 2016.

73 Baird, 2004.

74 Maia et al., 2010.

The issue of the increasing scale and complexity of the microphysics instruments ("Big Science") in the history of radioactivity through the experiences of nuclear reactions carried out by Rutherford. But few decades before, in the early days of radioactivity, instrumentation could be relatively simple even when experiments were rigorous and demanding. For example, Rutherford and Soddy were able to clarify the spontaneous emission in experiments in simple test tubes.

One of the conditions for obtaining data about nature is to be able to "see" it well, which in modern science means not only being able to observe and measure but also transform reality to better know it. We can say that in research in microphysics these objectives were not only fulfilled but also exceeded. This is the case with the knowledge about nuclear fission that was the basis for the atomic bombs, an important issue when discussing science and ethics, although it may be seen as external to the analysis of the paths of knowledge undertaken here.

Large-scale experiments as reactors and accelerators, which had become essential in the development of microphysical research, naturally required large teams of researchers with different skills as well as technicians, a fact that reveals another aspect of microphysics research: it required a large and great team.

Since the beginning of radioactivity, the formation of teams has been a determining factor to the development of work although the teams were smaller. Also in Portugal, the existence of a well-coordinated team was decisive in research on radioactivity. Although on a small scale, the Center for Physics Studies of the University of Lisbon presents some of the characteristics described, in particular precisely the capacity of constituting a cohesive team which allowed, in particular, to choose appropriate experiences and build the necessary scientific equipment.[75] The Center for Physics Studies has promoted research into nuclear physics and radioactivity, producing some remarkable results, taking into account the country's conditions, particularly those related to lack of funding. The team that carried out this work was coordinated by researchers who had trained in the Curie laboratory and who arriving in Portugal worked

75 Serra and Bragança Gil, 2010.

mainly in X-rays spectrography, setting up their devices by recovering old material, building radiation detectors and carrying out experiments to obtain some relevant results that they published. A part of the results obtained by the Centre researchers were relevant enough to be reported by Beyer.[76] Besides the experimental work the training of young researchers become a very important task in the Centre in such way that, in five years, four PhD thesis were carried out, what made this Centre a unique case in Portugal during the 1940's. But in spite its good scientific results it did not maintain its importance for a long time because the team was dispersed due by the politics of Salazar government.

6. Concluding Remarks

In this study, it was mainly sought to emphasize certain characteristics of research in radioactivity, rather than to make its history. Many of the facts and events reported evidently belong to the history but they were chosen so as to enable the perception of a structure in the way of doing research in radioactivity and microphysics. This structure, which was sought to be defined throughout the historical account, can be identified by some characteristics:

1. The inventiveness of the experiments of several researchers.
2. The leading role of experimental work, what was attempted to do through by reporting the work of Rutherford and his team.
3. The relationship between microphysics experiments and technological knowledge: experiments in radioactivity benefited from the technology but in turn were the source of new technologies.
4. The formation of research teams: the experimental dynamics transformed the formation of teams into a determining factor in current research.
5. The evolution towards the Big Science that was triggered in the 1930s in Rutherford's laboratory and that no longer stopped.

76 Beyer, 1949.

6. The exchange of knowledge among several disciplines that "share" radioactivity: a question only briefly addressed
7. The tragic consequences of the research on atom, which along with its benefits, places it in the area of "good and evil".

Some of these features although implicit in several points of the text were not explored in depth as is the case of the relationship with technology. Multidisciplinary and ethical aspects of radioactivity were also only approached lightly given their vastness.

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