Bernard Fernandez

Unravelling the Mystery of the Atomic Nucleus: A Sixty Year Journey 1896 — 1956

English version by Georges Ripka

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Foreword to the French Edition

Throughout my life as a nuclear physicist, spent in the laboratory probing the properties of the atomic nuclei, I was repeatedly confronted with the question: how did this idea, this concept, this understanding arise, and by what path was it reached? The question obviously concerns our understanding and formulation of physical theory but also, and this is all too often forgotten, by the development of instrumentation. The revolutionary changes in our understanding of physical phenomena, which took place in the span of a few decades of the first half of the twentieth century, concern both equally. In fact, momentous upheavals of physical theory, such as the formulation of quantum mechanics, were forced upon physicists, often against their will, by a variety of experimental data which obstinately refused to be accounted for by prevailing theories.

Curiously, I never found a book which really answered this question. The book of Abraham Pais, *Inward Bound*, is a wonderful work and an inexhaustible source of references, written more for specialists. But it is a history of the physics of elementary particles and not of nuclear physics which preceded it. It highlights the evolution of the theory, casting somewhat aside the history of instrumentation. The two-volume work of Milorad Mladjenović is well documented, but it addresses mainly physicists without really answering the question. Upon scrutinizing paper after paper, upon following the tracks of progress, dead-ends, questioning and controversy, which form the matter upon which science breads, I observed that every step forward, be it modest or fundamental, was the fruit of a necessity. It never entered ready-made into the mind of a physicist, even if he was a genius, and we shall encounter several. It was almost always the answer to a concrete problem.

This book describes how atomic nuclei were discovered, progressively probed and understood. It begins with the discovery of radioactivity by Becquerel in 1896. It is written in a nontechnical language, without mathematical formulas. However, it is not intended to be a popularization of a scientific work, which might attempt to convey the essentials by means of analogies. I wish each sentence to be legible by both full-fledged physicists and non-specialists. The latter may occasionally consult the glossary at the end of the book for words marked by the sign ◇. Footnotes offer punctual explanations and comments. References are listed at the end of each chapter. A detailed bibliography of all the cited books can be found at the end of this volume.

As far as possible, the narrative uses terms and concepts, such as rays, atoms, elements,… *in the sense they were used and conceived at the time,* and it follows their progressive and occasionally abrupt changes in meaning. Terms which were used at a given time were the most suitable and plausible working tools. It would be both silly and unbecoming to comment or criticize them from the point of view of one "who knows the end of the story." The reader, who knows more and better today, may find it occasionally surprising to be faced with a hypothesis considered to be a verified truth, only to find it discarded later.

I should add what this book *is not*. It describes only briefly the technical applications of atomic and nuclear physics. For example, it does not describe the history of nuclear power plants. However, a chronology of the development of the atomic bomb is given because its development caused a qualitative change in the research facilities after 1945.

It all started with the discovery of radioactivity by Becquerel in 1896. Radioactivity confirmed the reality of atoms and produced a profound change in the very concept of atoms. It later provided insight in to their structure and the existence of an inner nucleus. What at first appeared to be a simple black blur on a photographic plate prompted physicists to discover more in order to "lift a corner of the veil," according to the expression of Einstein. Progressively and due to relentless work and fertile imagination, new concepts were forged. Our knowledge of the atom greatly expanded during the 1930–1940 decade. The theoretical schemes upon which our present understanding is based were developed shortly before and shortly after the Second World War. That is where the history covered by this book ends, although it is a pursuing adventure.

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This work has benefited from the encouragement and active help of my close collaborators, particularly of my friends at the *Service de Physique Nucléaire* of the French Atomic Energy Commission, as well as of the *Direction des Sciences de la Matière*. I spent endless hours and days in numerous libraries searching for documentation and original publications. It is a pleasure to acknowledge the warm and friendly welcome of the librarians, whose competence and devotion were a great help.

Some faithful friends not only encouraged me but also accepted the task of making a critical reading of this work, namely the nuclear physicists Jean Gastebois and Georges Ripka as well as the nonphysicist Maurice Mourier and the nonspecialist scientist Philippe Lazar. The translation of Russian texts is due

to Anne-Emmanuelle Lazar. Finally Bernard Gicquel took the trouble to read and correct the translations of the German texts. A hearty thanks to them all!

Vanves, France
February 2006

Bernard Fernandez

Foreword to the English Edition

The present English version of the original book is the result of 3 years of fruitful collaboration between us. All the sections have been revised and often rewritten. Many references as well as the glossary have been reviewed and rewritten with English readers in mind. Indeed it should be considered as a second edition.

We would like to express our gratitude to Aron Bernstein and Philippe Lazar for their critical reading of the manuscript.

Vanves, France — Bernard Fernandez

Queyssac les Vignes, France — Georges Ripka

Contents

Radioactivity: The First Puzzles

Leurs métamorphoses sont soumises à des lois stables, que vous ne sauriez comprendre.

A. France, *La Révolte des anges*.

Their transformations are subject to stable laws which you could not comprehend.

The "Uranic Rays" of Henri Becquerel

Henri Becquerel, while searching for X-rays, discovers a radiation emitted by uranium. The scientific community shows no interest in such a weak and incomprehensible phenomenon with no practical applications.

On this Sunday morning, March 1, 1896, Henri Becquerel is working in his laboratory at the *Muséum d'Histoire Naturelle* in Paris. He is waiting in vain for the sun to come out [1–3] because he needs the intensity of sunlight in order to confirm some interesting observations made a week earlier and communicated to the *Académie des Sciences* on February 24. But in this never ending winter, the sky remains obstinately covered, day after day.

Becquerel is a distinguished physicist, born in a family with several generations of scientists [4, 5]. His grandfather, Antoine César, born in 1788, was admitted to the *École Polytechnique* in 1806. He distinguished himself as an officer in the Napoleonic armies. After the final fall of Napoleon in 1815, he left the army and began a successful scientific career, working on electricity, optics, phosphorescence, and electrochemistry. In 1829, he constructed the first constant current electric cell.

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He was awarded the prestigious Copley Medal of the *Royal Society* in London in 1837, and in 1838, he became member of the *Académie des Sciences.* In 1838, he held the first physics chair in the *Muséum d'Histoire Naturelle* in Paris. When he died in 1878, Henri Becquerel, his grandson, was 26 years old.

Becquerel's father was the second son of Antoine César, Alexandre Edmond Becquerel, born in 1820. Although he passed successfully the admittance examinations to both the *École Polytechnique* and the *École Normale Supérieure*, he chose to work as an assistant to his father in the *Muséum d'Histoire Naturelle*. In 1852, he became Professor at the *Conservatoire National des Arts et Métiers* and he was elected member of the *Académie des Sciences* in 1863. Upon the death of his father, he succeeded him as professor in the *Muséum d'Histoire Naturelle,* where he specialized in electricity, magnetism, and optics. His works on phosphorescence and luminescence [6] were published in 1959 and assembled in two books [7, 8], published in 1859 and in 1867. They remained a standard reference for half a century. He invented a device, called the phosphoroscope, with which he proved that fluorescence, which had been discovered by G. G. Stokes in 1852, was nothing but phosphorescence lasting for a very short time. Alexandre Edmond Becquerel died in 1891.

Henri (Antoine Henri Becquerel, according to his birth certificate) was born on December 15, 1852, in the *Muséum*, the home of his parents. In 1872, he was admitted to the *École Polytechnique*, where he met Henri Poincaré, who was to become one of the most famous scientists of the time. They develop a long-lasting friendship. In 1876, he graduated from the *Écoles des Ponts et Chaussées.* First, he became an instructor at the *École Polytechnique* and later an assistant naturalist in the *Muséum*. In 1889, at the age of 37, he was elected member of the *Académie des Sciences*, and in 1895, he became physics professor at the *École Polytechnique*.

Henri Becquerel, polite and friendly, is a clever and rigorous experimentalist. Akin to many French physicists at that time, he is more inclined to observation than to theoretical speculation. His research, so far, is devoted to optics, a family tradition. In 1876, Lucie Jamin, the daughter of the Academician J. C. Jamin, becomes his wife and gives birth to a son, Jean, in 1878. She dies a few weeks later at the age of 20. On August 1890, Louise Désirée Lorieux becomes the second wife of Henri and Jean is brought up as her son. True to the family tradition, Jean will later also be admitted to the *École Polytechnique* and elected member of the *Académie des Sciences.*

The Discovery

The experiments, which Becquerel is performing in 1896, are motivated by the discovery of "X-rays," which Wilhelm Conrad Röntgen [9–11] had made a few months earlier. Röntgen had studied the "cathode rays" produced by electrical discharges in gases. When a voltage exceeding a 1,000 V is created between two conductors placed in a container of gas maintained at low pressure, an electrical discharge occurs. The discharge consists of *cathode rays* emanating from the negatively charged conductor, called the cathode (We know today that cathode rays are electrons). Röntgen discovered that, when the cathode rays hit the glass wall of the container, they emit an unknown radiation which has a greater penetration power than light. He called them "X-rays." This discovery caused quite a stir and physicists, among whom Henri Becquerel, were quite excited. In the session of January 20, 1896 of the *Académie des Sciences,* two medical doctors, Paul Oudin and Toussaint Barthélémy, displayed X-ray photographs. Poincaré received a reprint of the paper of Röntgen. He and Becquerel were particularly impressed by the fact that the X-rays were emitted from the luminescent spot which was produced on the glass container by the impinging cathode rays. In a paper devoted to X-rays and published on January 30, 1896 in the *Revue Générale des Sciences*, Poincaré wrote:

> *It is the glass which emits the Röntgen rays and it emits them by becoming phosphorescent. Are we not then entitled to ask whether all bodies, whose phosphorescence is sufficiently intense, emit X-rays of Röntgen, in addition to light rays,* whatever the cause of the fluorescence is? *[12].*

This is precisely what Becquerel is investigating in his laboratory of the *Muséum d'Histoire Naturelle*. He is quite familiar with luminescence which he had studied at length with his father. Luminescent bodies are not spontaneously luminous but, when they are exposed to light, they radiate their own light, almost immediately[1] in the case of fluorescence, or within a variable laps of time, in which case the phenomenon is called phosphorescence.[2] Becquerel possesses thin strips of double uranium and potassium sulfate, and he is quite familiar with their phosphorescence which is intense but lasts only about a hundredth of a second. He then performs the following experiment, which he later described in a communication to the *Académie des Sciences*, dated February 24:

> *We wrap a Lumière photographic plate, composed of a bromide gel, between two sheets of very thick black paper, such that the photographic plate does not become veiled when exposed to sunlight during a whole day. On top of the paper sheet, we place a strip of a phosphorescent substance, and the lot is exposed to the sun during several hours. When the photographic plate is subsequently developed, the silhouette of the phosphorescent substance appears in black on the photograph [. . .] We are led to conclude from these experiments, that the phosphorescent substance emits a radiation capable of passing through the paper which is opaque to light [13].*

Becquerel exposes this assembled package to sunlight, the most intense source of light at his disposal. The following Wednesday, February 26, he attempts to make an X-ray photograph. He repeats the experiment, but this time, he slips a thin strip

[1]That is to say, within a time delay of the order of one hundred millionth of a second.

[2]The laps of time can vary from a thousandth of a second to several thousand seconds.

of copper, in the shape of a Maltese cross, between the phosphorescent uranium sulfate sheet and the photographic plate, the latter being again wrapped in thick black paper. He knows that the copper strip is opaque to X-rays, and he expects that, after a similar exposure to sunlight, a Maltese cross will appear in white on the developed photographic plate. He proceeds to expose this newly assembled package to sunlight in order to produce the phosphorescence. The sky is clear until 10 a.m. but obstinately remains clouded thereafter. The following day, the sun shines only between 3 p.m. and 7 p.m. when new clouds appear. Becquerel then puts the package into a drawer, pending better weather. The following 2 days remain grey. No sign of improvement on the following Sunday, March 1, when it even begins to rain [14].

Rather than wait, possibly several days more, Becquerel decides to develop the photographic plate in his drawer. He expects to obtain a weak picture because the plate was exposed to sunlight for a short time only, and the induced phosphorescence was expected to be weak. However, contrary to his expectations, the developed photographic plate shows that it had been intensely exposed. It also displays a somewhat blurred shape of the Maltese cross! Becquerel is surprised and, true to the clear-sighted and rigorous physicist he was, he repeats the experiment maintaining this time the assembled package in complete darkness. The photographic plate is again strongly exposed! On Monday, March 2, 1896, he presents the following note to the *Académie des Sciences*:

> *I insist on the following feature, which I consider very important and not in accord with the phenomena we might have expected to observe: the same crystalline strips, placed upon the photographic plates, under the same conditions and with the same screens, but protected from incident radiation and maintained in darkness, produce the same exposure on the photographic plate [. . .] I immediately thought that this action had necessarily continued in darkness [15].*

Henri Becquerel has just discovered what we call today *radioactivity*.

Is It Really Phosphorescence?

At first, Becquerel believes that the physical process which he is observing is phosphorescence produced by exposure to light and that it should therefore die out in time. In order to make sure, doubt being the physicist's best advisor, from March 3 onwards, Becquerel maintains his strips in darkness, and, from time to time, he checks their radiative power. Month after month, it persists, showing no sign of weakening. In November 1896, Becquerel notes:

> *. . . protected from any known radiation, [. . .] the substances continued to emit active radiation which penetrated glass and black paper, and this has been going on for 6 months for some samples and 8 months for others [16].*

He makes another strange observation: similar experiments performed with other luminescent substances fail to produce the effect [17]. However:

> *All the uranium salts which I have studied, whether they are, or not, phosphorescent, exposed to light, crystallized, melted or dissolved, gave similar effects;* I was therefore led to conclude that the effect was due to the presence of the element uranium in the salts[1], *and that the metal would produce a stronger effect than its compounds. The experiment was performed [. . .] and it confirmed this prediction; the photographic effect is notably more intense than that produced by a uranium salt [18].*

Becquerel insists that it does not matter whether the uranium salts are crystallized, melted, or dissolved because only the crystallized form is phosphorescent. The relation between the phenomenon he discovered and phosphorescence becomes increasingly doubtful. In other words, the "radiant" activity appears to bear no relation to the exposure of the substance to sunlight.

Although he continues to use the word "phosphorescence," Becquerel gradually gives up the original idea which led him to the discovery. To be faced with such a phenomenon, which occurs in a similar fashion independently of the chemical compound of uranium, was quite an extraordinary experience for a physicist or a chemist at the end of the nineteenth century. One thing, which chemistry had shown since Lavoisier, was precisely the fact that properties of chemical substances did not reflect the properties of the elements from which the substances are formed. Kitchen salt, for example, is sodium chloride and its properties are quite different from those of either sodium or chlorine. The radiant activity of uranium was both strange and unique.

What Is the Nature of the Radiation?

The terms "ray" or "radiation" are used to describe something which emanates from a source and propagates in a straight line, as sun rays do. In the paper announcing his discovery of X-rays, Röntgen wrote:

> *The reason why I allowed myself to call "rays" the agent which emanated from the wall of the discharge vessel, is partly due to the systematic formation of shadows which were observed when more or less transparent materials were placed between the apparatus and the fluorescent body (or the sensitive plate) [9].*

According to the theory of Maxwell, brilliantly confirmed experimentally in 1888 by Hertz, any sudden electric or magnetic disturbance becomes the source of an electromagnetic field$^{\diamond}$ which propagates in a straight line at the speed of light.

[1]Emphasized by the author.

This electromagnetic field is in fact light, visible light being nothing but a particular instance. Röntgen showed that X-rays propagate in a straight line and, in spite of the fact that they could neither be reflected nor refracted, he believed that they were electromagnetic waves, that is, a kind of light which is invisible to our eyes but which can be detected on a photographic plate (or on a luminescent screen).

In his second communication on the discovery of X-rays, Röntgen noted that they had the power of discharging electrified bodies [10], that is, that they allowed an electric current to pass through air, a feature which was confirmed by numerous other works [19–22]. Becquerel subjects his "uranium rays" to similar tests. For this purpose, he uses a gold leaf electroscope$^{\diamond}$. When they are electrically charged, the gold leaves repel each other. But when Becquerel places a piece of uranium in their vicinity, they gradually coalesce: the electroscope discharges itself, indicating that some electricity has escaped through the air:

> *I have recently observed that the invisible radiation emitted under these conditions has the property of being able to discharge electrified bodies which are subject to their radiation [23].*

This property will play a major role, as we shall see. Since it manifests itself by a measurable electric process, the radiation becomes detectable. This became the first detector other than the photographic plate.

A Limited Impact on Scientists and the Public

Whereas the discovery of X-rays aroused considerable interest among both physicists and the public, the "radiant activity of uranium" made a very limited impact on physicists and none on the general public. In the year 1896, more than 1,000 publications were devoted to X-rays, but barely a dozen to the radiation of uranium [24]. Indeed, X-rays provided the possibility to see the interior of the human body, the dream of medical doctors, who would not even have imagined such a possibility a year earlier. Furthermore, X-rays are easy to produce. They required a Crookes tube and a Rühmkorff coil which could be found in practically any lab. The 1897 issue of the *Almanach Hachette*, subtitled *Petite Encyclopédie populaire de la vie pratique*[1] noted:

> *It is truly the invisible which is displayed by the mysterious X-rays, which we all have heard about. To show the bone hidden under the flesh, the weapon or projectile buried in a wound; to read all the inside of the human body—perhaps even thoughts!—to count the coins through a carefully closed purse; to seek the most intimate confessions hidden in a sealed envelope; it all becomes child's play for any amateur. And what is required to perform such miracles? Precious little: an induction coil, a glass bulb and a simple photographic plate [25].*

[1] Little encyclopædia of practical life.

The radiation of uranium was far less interesting. For one thing, it was very weak: exposures lasting hours were required whereas, in 1897, 10 min were sufficient to produce an X-ray photograph (the first X-ray photograph, which showed the hand of Bertha, the wife of Röntgen, was obtained in 1 h). But most of all, nobody could see what the uranium rays could be used for. The case of the English physicist Sylvanus P. Thomson is quite instructive in this respect. He was also interested in X-rays, and, like Becquerel, he thought that they were linked to phosphorescence. He even observed, at about the same time as Becquerel, that phosphorescent uranium salts emitted a radiation, which he proposed to call "hyperphosphorescence." But Becquerel was the first to publish his observations. Thomson published his a few months later [26], in June 1896, and then he abandoned their study in order to devote his research to the study of X-rays. After November 1896, even Becquerel abandoned the study of uranium radiation for several years. With the experimental means available to him at the time, he could not see how to progress further.

Why 1896?

Becquerel used to say that radioactivity was bound to be discovered at the *Muséum*. He considered that his discoveries were "daughters of his father and grandfather; they would have been impossible without them." [27] However, in a lecture delivered at the University of Yale in March 1905, Ernest Rutherford claimed that the discovery could well have been made a century earlier:

> *In this connection it is of interest to note that the discovery of the radioactive property of uranium might accidentally have been made a century ago, for all that was required was the exposure of a uranium compound on the charged plate of a gold-leaf electroscope. Indications of the existence of the element uranium were given by Klaproth in 1789, and the discharging property of this substance could not fail to have been noted if it had been placed near a charged electroscope. It would not have been difficult to deduce that the uranium gave out a type of radiation capable of passing through metals opaque to ordinary light. The advance would probably have ended there, for the knowledge at that time of the connection between electricity and matter was far too meagre for an isolated property of this kind to have attracted much attention [28].*

Was Radioactivity Discovered by Chance?

When he developed his photographic plate on March 1, 1896, Becquerel certainly did not expect to see what he saw. Can we say that he discovered radioactivity by chance? Becquerel had designed an experiment with a well defined goal, namely, to observe a radiation, if it exists, similar to X-rays and emitted by phosphorescent substances. The lack of sunlight as well as his decision to develop the photographic plate admittedly played an important role. But his experiments would have led him, sooner or later, to the same discovery. The nature of a true physicist consists in being surprised by the right thing. In this respect, Becquerel left nothing to chance [29]. Better still, by mounting successive and rigorous experiments, he gradually showed that his initial idea was wrong, that the radiation was not linked to phosphorescence, but that instead, it was a truly new phenomenon linked to the presence of uranium. It is in this respect that he truly discovered radioactivity. Sylvanus Thomson had made the same observation in a similar fashion, but without persevering. Similarly, Abel Niepce de Saint-Victor, a French officer and amateur chemist, had observed that uranium salts could leave a trace on a photographic plate long after it had been exposed to sunlight, and he observed the same effect with tartaric acid. He published a number of papers between 1857 and 1867 on what he called "A new action of light." [30] But he always linked the observed effects to exposure to light: he did not discover radioactivity.

The discovery made by Becquerel was truly unexpected. But is that not the nature of every true discovery?

Polonium and Radium

A young Polish student and her French husband, working outside the French university establishment, discover two new elements, polonium and radium, which are considerably more radioactive than uranium. Their discovery rekindles research on radioactivity. Pierre and Marie Curie ask the crucial question: where do radioactive elements find the energy required for them to radiate?

Two years after the discovery of radioactivity by Henri Becquerel, the study of the "radiating activity" of uranium had ceased. But on the April 12, 1898, a young Polish woman, married to a French Physicist, delivers a communication to the *Académie des Sciences* which ignites a fire of interest which, this time, is likely to last.

Marya Skłodowska

Marya Skłodowska [31–34] was born in Warsaw in 1868 into a family with already three daughters, Sofia, Bronisława and Helena, and a son, Joseph. Her father, Władysław Skłodowski, teaches physics at the *Gymnasium* in Nowolipki street. Marya was born at a particularly dark time of Polish history. The defeat of the January 1864 uprising against Russian rule is followed by a ferocious repression. The Tsar decides to Russianize the country. Russian becomes the official language and the use of Polish is forbidden, even in schools. Władysław loses his job. After considerable difficulties, he succeeds in becoming a monitor in a boarding school with a small teaching duty. The family lives in poverty. Sofia dies from typhus in 1876 and Mrs. Skłodowska catches tuberculosis. She dies May 9, 1878, when Marya is barely 11 years old.

On June 12, 1883, at the age of 15, Marya graduates brilliantly from secondary school, earning a gold medal. But universities are closed to women. Her elder sister Bronia would also like to attend university and so the two sisters decide to make a deal: Marya will help Bronia financially to go to Paris by becoming a primary school teacher. Once Bronia gets the required diploma, she will in turn help Marya to join her in Paris. Seven years pass before Bronia, who has almost finished her medical studies and is married, can welcome her sister.

In the fall of 1891, in Paris, Marya attends the lectures of Gabriel Lippmann, Edmond Bouty, and Paul Appell at the *Sorbonne*. In July 1893, after living in considerable poverty for 2 years, she obtains a bachelor's degree in physics; she is the best student in her class. She goes back home to Poland for a vacation, fearing that she might not find the money to return to Paris. But, thanks to a heaven-sent subsidy (an *Aleksandrovič* grant of 600 rubbles), she returns to Paris and, in July 1894, she obtains a bachelor's degree in mathematics, graduating as second best in her class.

While preparing her bachelor's degree in mathematics, Marya begins to work in the laboratory of Gabriel Lippmann where she receives an assignment which pleases her: the *Société d'Encouragement de l'Industrie Nationale*[1] asks her to study magnetic properties of various steels. However, she lacks both the necessary funds and know-how. Then 1 day she mentions this to a Polish friend, Jósef Kowalski, physics professor in Freiburg, who was passing through Paris. He proposes to present her to Pierre Curie, a physicist who had done important work on magnetization.

Pierre Curie

Born on May 15, 1859, Pierre Curie is then 35 years old [35–38]. His brother Jacques is 4 years older. His father, Eugne Curie, was a medical doctor. Pierre never went to school: he was educated by his parents, some friends, and private tutors. He was described as a dreamy person who loved to walk in the country, where, thanks to his father, he could name every plant and animal he would come across. At the age of 14, his father entrusted him to a mathematics teacher, Albert Bazille. He passed the *baccalauréat*[2] at the early age of 16. The following year, he became an assistant to Paul Desains, a specialist of infrared radiation, after which he began to work in the laboratory of Charles Friedel, where he joined his brother Jacques. The two brothers discovered that some crystals, when compressed or elongated, emit electricity. Ten years, later the phenomenon was called piezoelectricity [39]. Pierre used this property to construct an extremely sensitive and precise electrometer.

In 1882, Pierre becomes an assistant at the newly founded *École Municipale de Physique et de Chimie Industrielle.*[3] Strictly, he does not have a lab at his disposal because the school's lab is reserved for the students. Fortunately, however, the director, Léon Schützenberger, a chemist who is also professor at the *Collge de France*, is an intelligent and liberal minded man who permits Pierre to pursue his personal research there. Pierre continues to work on crystallography. He believes that the symmetries displayed in the beautiful geometrical figures of crystals reflect deeper symmetries of the constituent atoms [40]. The importance which Pierre Curie attached to symmetry makes him appear today as a precursor [40, 41].

In 1891, he begins to study magnetization. He discovers and formulates what we call today the "Curie law"$^{\diamond}$ which exhibits a critical temperature (the Curie

[1]The society for the encouragement of national industry.

[2]Equivalent to the GCE both O and A levels.

[3]The municipal school of industrial physics and chemistry.

temperature◇) above which ferromagnetic substances lose their magnetization [42]. In spite of the fact that he holds no university position and has no official laboratory to work in, he becomes a well known scientist, especially abroad. It is therefore quite logical for Jósef Kowalski to suggest that Marya Skłodowska should consult him for her work on magnetization. They meet 1 day in the spring of 1894. The meeting becomes a mutual discovery and they are married a year later, on July 25, 1895, after some hesitation of Marya, to whom marriage means that she must give up the idea of returning to her father in her home country. She has the feeling of somehow betraying her country by getting married to a Frenchman and settling in France. But Pierre insists on the fact that she can continue her scientific work in France. And, after all, they are in love. . .

Polonium and Radium: Pierre and Marie Curie Invent Radiochemistry

Following the advice of Pierre, Marya, who now bears the name of Marie, completes her work on magnetization [43, 44] and searches for a subject for her PhD. This by itself is exceptional: so far, no woman in France had defended a PhD thesis in physics. Pierre suggests studying the "Becquerel rays" a subject that had been neglected for about 2 years. He even offers her a quartz piezoelectric electrometer with which she can measure the extremely weak electric current produced by the radiation of uranium. Although quadrant electrometers were available, his electrometers made it possible to measure the absolute value of the current in units of amperes (in fact tiny fractions of amperes). As Marie later stated:

> *We obtain thus not only an indication but a number which accounts for the amount of active substance [45].*

Where should she begin? Together with Pierre, Marie decides to find out whether substances other than uranium emit similar radiations. She soon discovers that thorium also radiates [46]. By coincidence, the German physicist Gerhard Schmidt published only a week earlier his observation that thorium was "active," that is, it emitted radiations [47]. However, the attention of Marie is attracted to a small detail. In practically all the cases she had studied, the activity of the uranium compound was precisely that which she could calculate, knowing the amount of uranium in the sample. She finds, however, one exception: two uranium minerals, namely, pitchblende (uranium oxide) and chalcolite (a copper and uranyl phosphate), are more active than what their uranium content would grant. She sees in this remarkable feature a hint that these minerals contain an element which is far more active than uranium. This is where the electrometer of Pierre turns out to be useful because it makes it possible to measure precisely weak currents of the