Rediscovery of the Elements

Madam Curie

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Fig 1. In Warsaw at 16 Freta Street, at the north end of the Old Town, is the Maria Curie Museum (N52° 15.09 E21° 00.51) (building to the left). The museum has exhibits on Maria Curie's personal life (e.g., her clothing apparel, bicycle, furniture) and her professional life (scientific apparatus used in her research); on her family including a large pictorial family tree; and on radiation and nuclear chemistry; and minerals associated with radioactive elements. Maria Sklodowska was born in this house, and her mother ran a school here.

Introduction. Hardly anyone needs an introduction to Marie Curie (1867–1934).[1-3] She was the first woman to win a Nobel Prize, and the first person to win two Nobel Prizes. She and her husband Pierre (1859–1906) captured the imagination of the scientific and popular world with their discovery of radium and polonium. She endured tragedy and depression when her husband was killed in a traffic accident, and survived to continue her work for another 28 years before succumbing to radiation-induced cancer. In spite of her fame, she never fell to pride; Einstein, a close friend, once said "Marie Curie is, of all celebrated beings, the only one whom fame has not corrupted."[1a] A daughter and son-in-law (Irène Joliot-Curie 1897–1956 and Frédéric Joliot-Curie 1900–1958) went on to win a Nobel Prize as well (1935). Marie Curie's legacy consists not

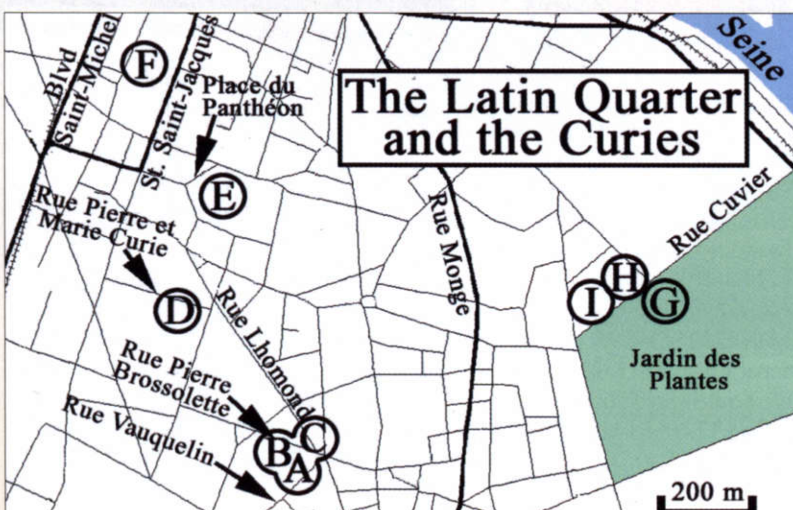

Fig 2. The important activity of the Curies was in the Latin Quarter of Paris, situated on the Left Bank (south side) of the Seine River. (A) The modern entrance of ESPCI, 10 Rue Vauquelin (N48° 50.47 E02° 20.86). (B) Historic location of "The Shed' in the courtyard of EPCI (N48° 50.50 E02° 20.83). (C) Entrance of EPCI before 1932, 42 Rue Lhomond (N48° 50.52 E02° 20.87). (D) Institut Curie and Curie Muséum, 11 Rue de Pierre et Marie Curie (N48° 50.66 E02° 20.67). (E) Panthéon, where the Curies are interred, Place du Pantheon (N48° 50.78 E02° 20.72). (F) Sorbonne courtyard (N48° 50.90 E02° 20.60). (G) Maison de Cuvier, where Becquerel discovered radioactivity, Jardin des Plantes (N48° 50.67 E02° 21.44). (H) Curie's later lab, 12 Rue Cuvier (N48° 50.68 E02° 21.37). (I) Pierre Curie's birthplace, 16 Rue Cuvier–N48° 50.66 E02° 21.34. (For geographical locations beyond the limits of this map, see Note 3.)

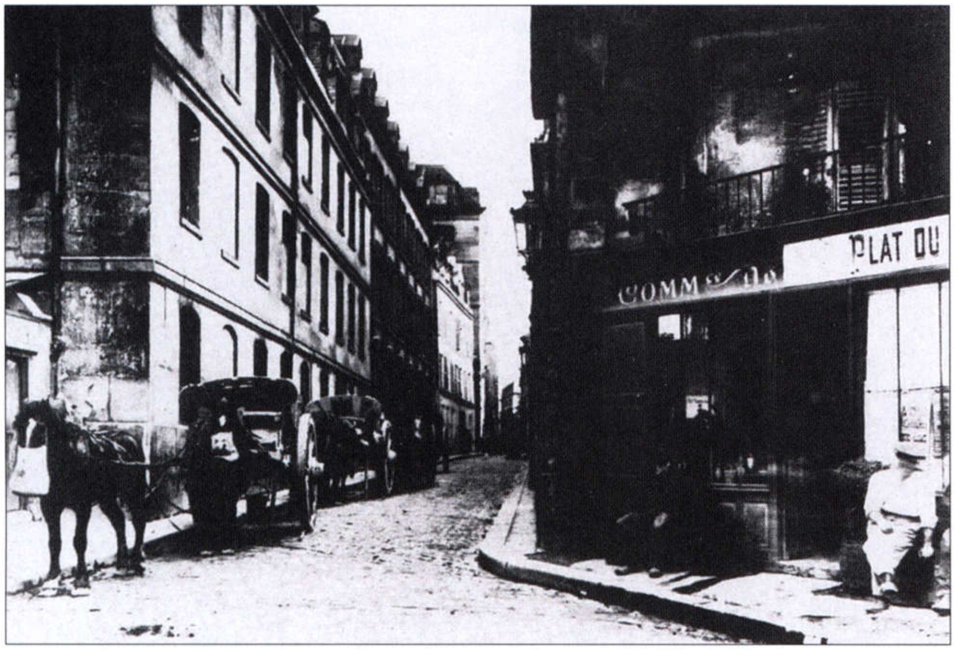

Fig 3. This is the appearance of EPCI (École de physique et de chimie Industrielles) at the time of the Curies, 42 Rue Lhomond. One can visualize tons of burlap bags of uranium ore being brought by horse-drawn cart to the entrance (behind the horse's head). EPCI was founded in 1882, when Pierre Curie joined the faculty.

only of scientific achievement, but also a supreme example promoting equality of women in the scientific workplace.[1]

The Discovery of Polonium and Radium. Maria Salome Sklodowska (Note 1) was the youngest daughter of Bronislawa neé Boguska and Wladyslaw Sklodowski, teachers in Warsaw, Poland. The house where Maria was born is now a museum (Figure 1). She saved her money working as a governess to follow her sister Bronya to Paris; Bronya studied at the School of Medicine before returning to Poland. Maria matriculated in the Sorbonne in Paris in November, 1891, and received masters degrees in 1893 (physics) and 1894 (mathematics), ranking first and second, respectively in her class (for a map of the Curies' activities in Paris, see Figure 2).

Maria's original plan was to return to Poland after completion of her studies, but she married Pierre Curie in 1895. Pierre was an instructor of physics at the EPCI (École de Physique et Chimie Industrielles (Figures 3 and 4), and therein developed a love story of a couple that shared happiness and scientific achievements until Pierre's tragic death in 1906.

In March, 1896, Henri Becquerel (1852–1908), professor at the Muséum National d'Histoire Naturelle, discovered that uranium salts (potassium uranyl sulfate) emitted invisible rays that passed through black paper and aluminum or copper sheets and exposed photographic plates.[4] This discovery was in a laboratory in the home of Georges Cuvier, renowned naturalist of the Muséum; this site still exists and is marked by a plaque (Figure 5).

The same year Maria and Pierre married, he received his doctorate on magnetism (the Curie point, the temperature at which a metal loses its magnetism, is named after him) and he was promoted to professor. Maria wanted to pursue a doctorate as well. The popular topic of the day was X-rays, also discovered the year of their marriage (by W. C. Röntgen), but Maria was already showing her independent temperament by selecting a subject that would be her own, and in 1897 she chose the study of uranium rays as her dissertation topic.

On the huge Periodic Table at St. Petersburg[5d] are inscripted Mendeleev's words [translated] "To do science, one must measure." Chemistry has well embraced this tenet since Lavoisier, who launched the "New Chemistry."[5c] Maria realized that in order to study uranium rays, she had to find a way to measure them quantitatively. (The Geiger counter was not invented until 1908, by Hans Geiger and Ernest Rutherford in Manchester, England). Becquerel had noticed that uranium rays not only fog photographic plates, but they also ionize surrounding air—detected, for example, by a gold-leaf electroscope, where two hanging gold leaves repel one another when an electrified rod touches them. Realizing neither fogged plates or repelling gold leaves would easily lend themselves toward quantification, Maria sought another method.

Maria decided to measure the amount of ionization by measuring the induced electric charge in an ionization chamber. Maria was given an unused bricked-in storeroom in the EPCI to conduct her studies. Carefully she would balance the ionization chamber voltage with that induced by the piezoelectric quartz apparatus designed by her husband (Figure 6).

Maria studied several uranium and uranium compounds and came to the conclusion that

Fig. 4. Modern ESPCI (École supérieure de physique et de chimie Industrielles), built in 1932; southward view from Rue Pierre Brossolette. (The entrance to the modern building is shown in Figure 9). The name EPCI was changed to ESPCI in 1948.

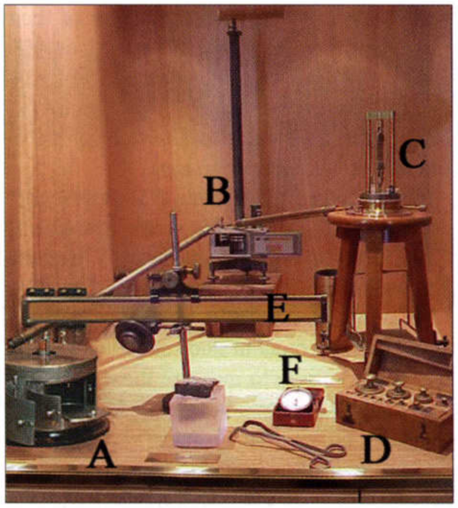

Fig. 6. This is the piezoelectric quartz balance, displayed in the Curie Muséum in Paris, used by Marie Curie to measure the ionization (and thus radioactivity) of minerals and chemical preparations. This Rube Goldberg contraption was engineered by the sheer genius of Pierre Curie in the days before electronics and the Geiger counter. The sample was placed in the ionization chamber A, in which the atmosphere becomes charged (precisely as in a modern smoke detector), whose voltage is measured by the electrometer B which is nulled out by the piezoelectric quartz C (the piezoelectric effect was discovered by Pierre and his brother Jacques in 1880) whose induced voltage is varied by weights D. The null point is detected by a light reflected off a mirror mounted on the electrometer onto a screen E as varying weights (from the set D) hanging from the quartz crystal induce the counter voltage. A chronometer F is used to measure the time it takes to saturate the ionization chamber. Also on exhibit in the foreground are pitchblende and forceps. The utter patience and supreme skill of Maria Curie was necessary to gather good data; a hasty or heavy hand would break the delicate wires suspending the weights.

Fig. 5. Maison de Cuvier, where Becquerel discovered radioactivity. A plaque (on the chimney) reads [translated]: "In the laboratory of applied physics Becquerel discovered radioactivity March 1 1896." Becquerel called the radiation "uranium rays"; Maria Curie coined the word "radioactivité." Behind the Maison de Cuvier is the later Rue Cuvier laboratory of the Curies (not in view).

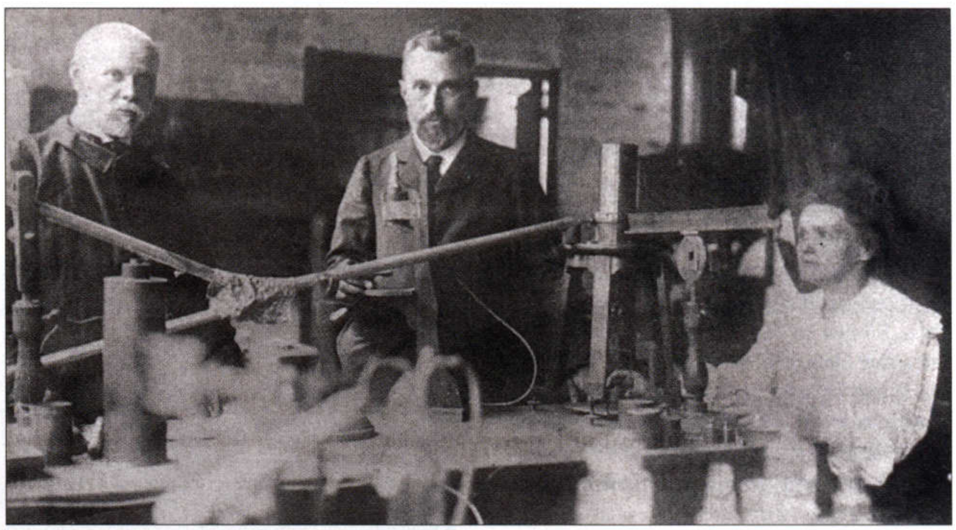

Fig. 7. This photograph appeared in the first issue of the journal Le radium *(January 1904) and shows the authors of the original 1898 article[10] announcing the discovery of radium. As Gustave Bémont (left) and Pierre Curie look on, Maria Curie is making a measurement. Frequently, particularly in websites but also in scientific journals, the person to the left is incorrectly identified as the "assistant Petit," but this has been proven to be false by the emergence of the passport photo of Bémont.[2b] Even further dishonoring the contribution of Bémont, the left-hand portion of the photograph is frequently cropped out. The photograph was taken in the first laboratory of the Curies, the storeroom in the main building on Rue Lhomond, (and not in "The Shed" as is frequently misstated)*

both the *form* (element, compound) and the *surrounding conditions* (temperature, pressure) had no effect on the amount of radiation. Therefore, she concluded, radiation must be an *atomic* property, dependent only on the amount of uranium present—a critical understanding for future work with radioactive compounds.

Were other elements radioactive? Maria went through "every known element" as she rummaged through the extensive collections of the Muséum National d'Histoire Naturelle, and found another element—thorium.[6]

What about native minerals? Serendipitously Maria studied minerals in their native state "just to be sure," and she got a surprise—pitchblende (uranium ore, mostly uranium oxide) itself was four times as active as the amount of uranium it contained. She tried other minerals, and some of them also were more active than the amount of uranium and thorium present. Was there an impurity or was this a property of the native mineral itself? She compared native chalcolite (an archaic name[7] for the green mineral torbernite[8] $Cu(UO_2)_2(PO_4)_2.8H_2O$), with artificial torbernite (chalcolite) she prepared from uranium and copper phosphate. The native torbernite was twice as active as the laboratory torbernite. She concluded torbernite had microscopic quantities of a new element, and so must pitchblende. There must be a new element in uranium ore!

By now Pierre had taken notice of Maria's fascinating work, and he abandoned his own research on crystals so that there would be "two

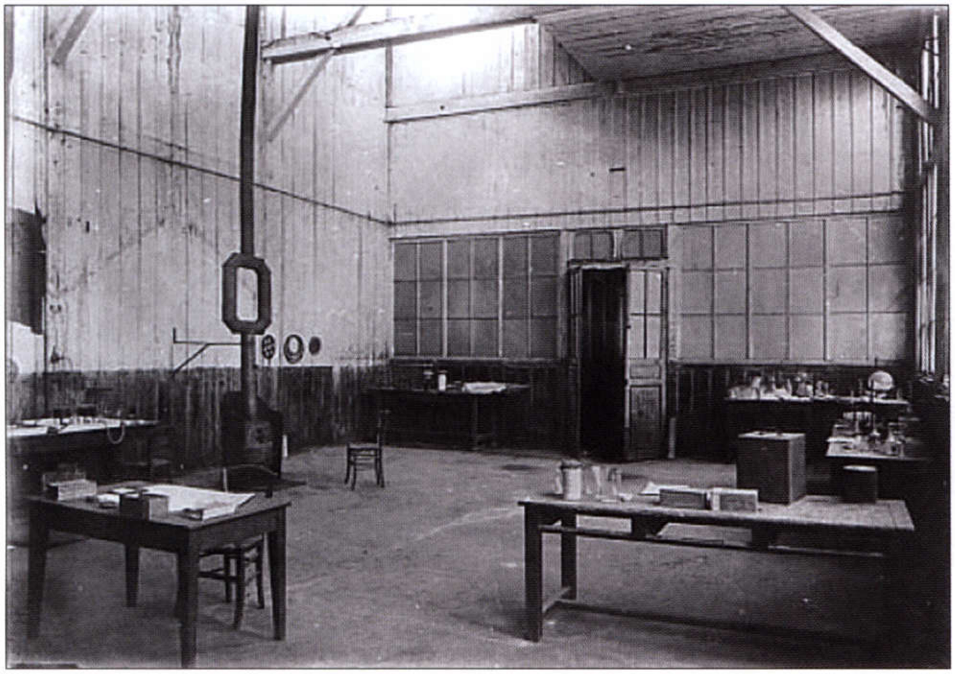

Fig. 8. This is a photograph of "The Shed," used 1899–1904, to process tons of pitchblende to concentrate radium and polonium; actinium was also discovered (Note 2).

Fig. 9. The modern entrance at 10 Rue Vauquelin. Through the entrance and to the right was "The Shed." An old plaque above and to the right of the doorway reads [translated] "In 1898 in a laboratory of this school Pierre and Marie Curie, assisted by Gustave Bémont, discovered radium." The laboratory referred to here is not "The Shed" but instead the storeroom shown in Fig 7. This plaque was on the old building (Figure 3) before it was transferred to the modern building (Figure 4) in 1932. Bémont was not destined to share the Nobel Prize because only three recipients could receive the prize per year in a given category, which in 1903 went to Becquerel and the two Curies. Bémont did not move with the Curies to their new laboratory on Rue Cuvier, and he faded into historical obscurity.

heads, four hands"[1c] to attack the problem. Just as previous chemists had *spectroscopically* detected and determined the concentrations of new elements in their chemical manipulations,[5a] the Curies pioneered the radiation method of following the journey of an element in a laboratory analysis. She guessed, there might be 1% or so in the ore. Little did they know that there would be *several* hidden elements and they would comprise about a *millionth* of a percent!

They chose pitchblende, the most common uranium ore, for their extensive search. Proceeding through classical analytical schemes, they observed that there were *two* fractions which had radioactivity—the bismuth and barium fractions. By July 1898, they announced an enhanced radioactivity level in their concentrated bismuth fraction, 400 times the radioactivity of uranium. "We have found a new element," Pierre and Maria announced. They named it "polonium" after her beloved native country.[9]

After the usual European summer vacation they returned to Paris and to the barium fraction. Enrichment of their ore proved tricky, and they obtained help of Gustave Bémont, director of the chemistry laboratory of EPCI (Figure 7). They also enlisted the help of Eugène Demarçay, the undisputed master of spectroscopic analysis.[5a] In December 1898, the two Curies and Bémont announced they had obtained a radium fraction whose radioactivity level was 900 times that of uranium.[10] They named the new element *radium*. Immediately following their article was a contribution by Demarçay[11] with a spectroscopic corroboration [translated]: "The presence of a line at 3814.8 confirms the existence of a small quantity of a new element in the barium chloride fraction of M. and Mme. Curie." It indeed is fortunate that it was a small quantity; when an attempt was made to determine the spectrum of pure radium chloride several years later, it short-circuited the spectrograph! (Demarçay had also searched the bismuth fraction to confirm polonium, but saw no new lines).

The Curies' discoveries made for sensational news, but the fact remained that no one had ever seen polonium and radium. There were many doubters—Lord Kelvin maintained for several years that radium was nothing more than "a compound of helium."[1b] Pierre and Maria set themselves the goal of producing observable amounts of their discovered elements.

The Curies had tried to determine a relative atomic mass of their new elements, but their determined values was barely different from the carrier elements (barium and bismuth). It was obvious that in order to produce quantifiable amounts, they needed more ore—*much* more—and a large laboratory space to process it. The ore they obtained by skillful negotiations with the Austrian government, who sent processed uranium ore which had been dumped near the Urangelbfabrik in Joachimsthal.[5e] For laboratory space they first asked the Sorbonne, where Maria obtained her degrees. This institution was not helpful; they had historically been short of laboratory facilities even for themselves.[12] The EPCI had no better facilities, but allowed the Curies to occupy an abandoned dissecting laboratory for the École de Médicine, which was directly across a small courtyard from the storeroom where Maria had been conducting her studies. The dissecting laboratory was a wooden building—called "le Hangar" ("The Shed")—with an asphalt floor and a glass-roof; it leaked when it rained, was stifling hot in the summer, and freezing in the winter (Figure 8). Pierre was not sure he wanted to pursue such a challenging goal under these trying conditions, but Maria was driven, and they committed themselves. Later, "The Shed" was described by Nobel Laureate Wilhelm Oswald as "halfway between a stable and a potato cellar" which he thought was a hoax until he saw the laboratory equipment.[2b] Maria was to write later, "I would be broken with fatigue at the day's end . . . Yet it was in this miserable old shed that the best happiest years of our life were spent, entirely consecrated to work."[1e]

By early 1899, burlap sacks were arriving at the Rue Lhomond address (Figure 3) and were stacked in the courtyard. Inside the sacks were the dark powder mixed with pine needles and dirt. Maria ran her hands through the precious brown ore, soiling her hands—but to her it was gold. Over the next four years the Curies worked through tons of ore in a heart-wrenching and heroic effort to extract the precious radium. (The other other element, polonium, had been more problematic, owing to its shorter half-life—Ra-226 has a half-life of 1260 years and polonium-210 has a half-life of 139 days.) But eventually they were obtaining sufficiently enriched samples that their laboratory was becoming lined with bottles which would glow bluish during the night. She would love to sit in the darkness, with an "evening of glowworms, this magic."[1c] Today "The Shed" is gone, the victim of expansion of EPCI in 1932 (Figures 9 and 10).

Marie received her doctorate in 1903, founded on her work which won that same year a Nobel prize shared with Becquerel and her husband Pierre. Without a doubt Maria's Ph.D. dissertation was a masterpiece,[1d] even considered by some historians to be the most important physics Ph.D. dissertation ever written.[13] Pierre and Maria were now famous. The elitist Sorbonne, which previously had snubbed Pierre, was now shamed into giving him a professorship and a new laboratory at the Rue Cuvier branch of the university, which opened by 1905.

But all of this recognition and success came at a cost: working with radium through the years had an extremely injurious effect on both of them. Their fingers were hardened and cracked, and they complained of numbed fingertips. Pierre's legs ached and he was in pain constantly. Sometimes his legs shook so that he could not stand. It is believed that this disability was at least partially responsible for his accident of 19 April 1906. On the afternoon of this day while performing errands he was walking on the Rue Dauphine by Pont Neuf, when he was run over by a wagon and killed. Witnesses said he darted out and stumbled, grabbed at the horse to stabilize himself which caused the horse to panic and rear. He fell underneath the heavy carriage, laden with military uniforms, which the driver could not stop despite frantic efforts. Death was instantaneous and Pierre suffered no pain.

Maria, who had loved her husband dearly, missed him daily for the rest of her life. The biographer Susan Quinn reports that Maria wrote 24 years later,[1d] "I lost my beloved Pierre, and with him all hope and support for the rest of my life." But Maria decided to continue on the work she and her husband had begun. She took over Pierre's academic duties and on November 5, 1906, became the first woman ever to teach at the Sorbonne. Her research team at Rue Cuvier prospered; with her colleague André Debierne (note 2), she obtained metallic radium and determined atomic mass for radium of 225.35, remarkably close to the modern value of 226.0. With Debierne, she more fully characterized polonium and actinium, finding spectral lines for each. She was given another Nobel Prize, this time in chemistry, in 1911, for her researches on radium. For the rest of her life she continued research on radium and its beneficial effects to mankind. She moved into the new Radium Institute in 1914, which today serves as the Curie Museum in Paris (Figure 11). She died from pernicious anemia in 1934, induced by her work with radium.

Fig. 10. The former location of "The Shed" is identified by the white lines on the ground. Now the area is used as a motorcycle parking lot. The adjoining courtyard to "The Shed" was important, because the huge vats with their toxic fumes needed to be outside.

Both Pierre and Maria were buried in Sceaux, the home of his parents. In 1995 their remains were transferred to the Panthéon in Paris, and in an extravagant ceremony 21 April 1995, Francois Mitterrand (President of France) and Pierre-Gilles de Gennes (Nobel Laureate, Director of ESPCI) gave presentations in tribute to the famous couple (Figures 12).

The Mystery of Radioactivity. What makes some elements radioactive? What is the nature of radioactivity? Maria Curie originally had considered the possibility that the atoms were self-destructing, but both Henri Becquerel and Pierre Curie continued to believe in the immutability of atoms; they thought that radioactive elements had absorbed energy somehow in their past. Meanwhile, the British were developing their own model which involved transmutation of the elements, which proved to be the key to atomic structure, atomic numbers, and isotopes. This story will be told in a future article in *The HEXAGON*.

EDITORS' NOTE: It is with regret that space does not allow us to tell any more of the life of Maria Curie, which deserves much fuller treatment, particularly during her years after Pierre died, when so much of her work was done to develop beneficial uses of radium. Ref 1 lists some of the resources for those who might use to explore her rich life during this period of time, as well as the history of radium with all its benefits and some of its tragically unhealthy properties.

Acknowledgments.

The authors are indebted to Drs. Pierre-Gilles de Gennes and Michel Lagues of ESPCI, who extended gracious hospitality and furnished much information concerning not only the Curies, but also other scientists associated with "Rediscovery," notably Louis Nicolas Vauquelin (chromium, beryllium) and Georges Urbain (lutetium).

References.

1. Suggested readings are (a) C. K. McClafferty, *Something Out of Nothing. Marie Curie and Radium*, **2006**, Farrar Straus Giroux, NY; (b) B. Goldsmith, *Obsessive Genius. The Inner World of Marie Curie*, **2005**, Norton, NY; (c) E. Curie, *Madame Curie. A Biography by Eve Curie*, trans. V. Sheean, **1937**, The Literary Guild of America, NY; (d) S. Quinn, *Marie Curie. A Life*, **1995**, Simon & Schuster, NY.

Fig. 11. The Radium Institut/Curie Musésum on Rue Pierre et Marie Curie. Numerous exhibits detailing the lives of the Curies are presented, as well as scientific apparatus of theirs and of the next generation Irène and Frédéric Joliot-Curie.

Fig. 12. The Panthéon, created by Napoléon to honor "great men, [from] the grateful homeland" where the remains of the Curies are interred in sarcophagi in the subterranean chambers.

(e) *Autobiographical notes & Pierre Curie*, M. Sklodowska-Curie, **2006**, Dom Wydawniczo-Promocyjny GAL, Warsaw.

2. Excellent factual accounts of the scientific accomplishments, extensively referenced and correcting common errors in the literature and popular websites, are R. F. Mould, (a) *Brit. J. Radiology*, **1998**, *71*, 1229–1254; (b) *Med. Phys.*, **1999**, *26(9)*, 1766–1772.
3. A masterful movie that uses amazingly accurate stage sets and correct chemistry to describe the hopes, disappointments, and joys of scientific endeavors is *Madame Curie* with Greer Garson as Marie Curie and Walter Pidgeon, made by MGM in 1943, and is recommended strongly by the authors to be used in science classes.
4. H. Becquerel, *Comptes rendus*, **1896**, *122*, 501–503. This phenomenon had actually been observed with uranium nitrate by Sylvanus Thomson (1851–1916), president of the Röntgen Society of London, just a few weeks previously.[2] However, Thomson did not extend his researches, as did Becquerel, to understand that prior exposure to light was not necessary [J. R. Partington, *A History of Chemistry*, **1961**, Vol. IV, Macmillan, London, 936].
5. J. L. Marshall and V. R. Marshall, *The HEXAGON of Alpha Chi Sigma*, (a) **2002**. *93(4)*, 78-81; (b) **2003**, *94(2)*, 19-21; (c) **2005**, *96(1)*, 4-7; (d) **2007**, *98(2)*, 23-29; (e) **2008**, *99(4)*, 68-71.
6. Mme Sklodowska Curie, *Comptes rendus*, **1898**, *127*, 1101–1103. This observation was previously made, unknown to the Curies, independently by G. C. Schmidt, Verh. Phys. Ges. Berlin, **1898**, *17*, 14-16.
7. P. Bayliss, *Glossary of Obsolete Mineral Names*, **2000**, The Mineralogical Record, Tucson AZ.
8. *Dana's New Mineralogy*, 8th Ed., **1997**, John Wiley & Sons, N.Y.
9. M[onsieur]. P. Curie and Mme S. Curie, *Comptes rendus*, **1898**, *127*, 175–178.
10. M[onsieur]. P. Curie, Mme P. Curie, et de M[onsieur]. G. Bémont, *Comptes rendus*, **1898**, *127*, 1215–1217.
11. E. Demarçay, *Comptes rendus*, **1898**, *127*, 1218.
12. A. J. Rocke, *Nationalizing Science: Adolphe Wurtz and the Battle for French Chemistry*, **2001**, MIT Press, Cambridge MA.
13. *Nobel Laureates and Twentieth Century Physics*, M. Dardo, **2004**, Cambridge, MA; H. C. Lehman, J. Gerontol., **1964**, *19*, 157–164.
14. A. Debierne. *Comptes rendus*, **1899**, *129*, 593-595; **1900**, *130*, 906-908.

Notes.

Note 1. Maria commonly signed her name "Manya" in correspondence. The name Marie was given to her by the French authorities as her fame was established in Paris. The maiden name "Sklodowska" incorporates the Polish letter "stroke l" and is pronounced as English "'w." Thus, her maiden name is pronounced "skwa-DOHV-ska."

Note 2. Debierne (1874–1949) was a constant companion of the Curie's since 1900. He discovered actinium[14] as a radioactive component in the titanium fraction of pitchblende processed at "The Shed," but published this work as being done at the Sorbonne, the site of his major professor Charles Friedel (1832–1899). Debierne took over the Radium Institute in 1934 upon Maria Curie's death and was succeeded in this post 1949 by the daughter of Maria Curie, Irène Joliot-Curie.

Note 3. Geographical locations not included on the map (outside the Latin Quarter):
1895–1898: Curies lived at 24, rue de la Glacière, during discovery of radium–N48° 50.13 E02° 20.70 [PLAQUE].
1899–1906: Curies lived at 108 Kellerman–N48° 49.16 E02° 20.67 (house now gone).
1900–1906: Sèvres, Maria Curie taught at the École Normale Supérieure ("for young girls"); building now Le Centre International d'Etudes Pedagogique–1, Avenue Léon Journault–N48° 49.46 E02° 12.98.
1906–1912: Mme Curie and Pierre's father lived at 6, rue du Chemin de Fer in Sceaux (now Rue Jean Mascré)– N48° 46.91 E02° 17.68 [PLAQUE]
1912–1934: Mme Curie lived at 36 Quai de Bethune– N48° 51.06 E02° 21.37. [PLAQUE]
Home of Pierre's parents in Sceaux, 9 Sentier de Sablons (now Rue Pierre Curie)–N48° 46.58 E02° 17.12. [PLAQUE].
The burial plot of Pierre's parents, Eugène (1827–1910) and Sophie-Claire née Depouilly (1832–1897) Curie, are in the northeast corner of the Cimetière de Sceaux– N48° 46.81 E02° 17.05. (Pierre and Marie Curie were buried here until their remains were transferred to the Panthéon in Paris in 1995).
Pierre Curie killed on Rue Dauphine at Pont Neuf– N48° 51.36 E02° 20.42.