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REVIEW

The Periodic Table

SUSANTA LAHIRI[1,2,*] and ASHUTOSH GHOSH[3,4]

[1] Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata 700064, India.
[2] Homi Bhabha National Institute, BARC Training School Complex, Anushaktinagar, Mumbai 400094, India.
[3] Rani Rashmoni Green University, Tarakeswar, Hooghly, India.
[4] Department of Chemistry, University of Calcutta, 92 Acharya Prafulla Chandra Road, Kolkata 700009, India.
*Corresponding author. E-mail: susanta.lahiri@saha.ac.in

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Abstract. In this article, a historical overview of the development of the Periodic Table has been sketched. After Mendeleev published his Periodic Table in 1869, 55 more elements have been discovered. Of these 55 elements, 35 are radioactive; most of them never existed on Earth earlier. The excitement of the discovery of these unstable elements has been emphasized in this article. In conclusion, the dynamicity of the Periodic Table and its future have been projected.

Keywords. Periodic Table—radium—polonium—inert gas elements—actinides—superheavy elements.

1. Introduction

A Google search for “The Periodic Table” yielded 13,00,00,000 entries in 0.48th of a second. UNESCO declared the year 2019 as the International Year of the Periodic Table (IYPT). According to IYPT “The Periodic Table of chemical elements is one of the most significant achievements in science”. IYPT-2019 was formed by the support of the International Union of Pure and Applied Chemistry (IUPAC) in association with the International Union of Pure and Applied Physics (IUPAP), the European Association for Chemical and Molecular Science (EuCheMS), the International Council for Science (ICSU), the International Union of History and Philosophy of Science and Technology (IUHPS) and the International Astronomical Union (IAU). The official partnership for celebrating 150 years of the Periodic Table of chemical elements itself signifies that the impact of the Periodic Table is not only restricted to chemistry, but spreads over physics, biology, medicine, molecular science, technology, and even astronomy. In fact, the Periodic Table crossed the boundary between science and humanities when historians and sociologists became interested in knowing the catalytic action of society for such a development in science.

The chemical elements act as a bridge between Earth and astronomical objects. Billions of years of galactic history is embedded in the chemical elements. The Big Bang happened 13.77 billion years ago, and just after 10^{-6} of a second, quark-to-hadron transition took place, creating protons and neutrons. The deuteron, helium and lithium were created one second after the Big Bang. Along the timeline, about 4.5 billion years ago, Earth, perfect planet for sustaining life as we know it, was born. Apart from plenty of hydrogen and oxygen in the form of water, Earth contained several elements like Si, Al, Fe, Ca, Na, K, Mg, Ni in its crust, mantle and core (Lutgens and Tarbuck 2000). One of the major sources of Earth’s internal heat is radioactive decay. The primordial radioisotopes, like ^{40}K, ^{238}U, ^{235}U, ^{232}Th, were present from the birth of this planet. Interaction of cosmic rays with the upper atmosphere of Earth produced

*For correspondence
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^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl, etc. Meteorites, interplanetary dust from the asteroid belt, and cometary clouds (like Kuiper belt) injected many elements into Earth. Some nearby supernova (SN) explosions might also have injected SN-produced radionuclides like ^{182}Hf, ^{146}Sm, etc. Therefore, all the elements known today (except some which were never present on our Earth or in the Universe) were present since the beginning of Earth.

About 3.8 billion years before the origin of life on this Earth, 2.5 million years BP humans evolved in Africa and about 200000 years before *Homo Sapiens* evolved in East Africa. Only 70000 years before *Homo Sapiens* evolved to a more elaborate structure called cognitive revolution. The agriculture revolution took place 12000 years BP. Permanent settlement started from the time of agriculture revolution (Harari 2015). What about elements? Did *Homo Sapiens* recognise the elements and their utility?

The people of the Harappan civilization (2600 BCE) used metals and minerals. Lead and silver rings were common artefacts in Mohenjo-Daro, Shahr-i-Sokhta (3200–1800 BCE) and other old civilizations (Law 2005). Three varieties of lead (PbO, $PbCO_3$-$PbSO_4$ and PbS) were found at Harappa and these were used to make different varieties of pigment. The dancing bronze figure of Mohenjo-Daro is a famous historical artefact. The first coins in history were found in the seventh century BCE in western Anatolia (Harari 2015). Many elements including their uses were known from the beginning of civilization. For the rest of the elements, humans had to wait many centuries, till science was developed and more elements were discovered by scientists. Phosphorus is claimed to be the "first discovered" element, in 1669 in Germany.

In the universe, the lighter elements were created first, and then the heavier elements. Hydrogen was created at the time of the Big Bang; the deuteron was created just one second after the creation of hydrogen. Interestingly, this order is not seen in the chronology of the discovery of elements. The lightest element was unknown till 1766, when Henry Cavendish, a British physicist and chemist, demonstrated the properties of water (hydro) forming (gene) gas, "hydrogen". The heavier form of hydrogen, deuterium (in today's terminology isotope of hydrogen), was discovered in 1931 at Columbia University by the American physicist, chemist and Nobel Laureate Harold Urey. A timeline of the discovery of elements is shown in Figure 1.

UNESCO celebrated 2019 as 150 years of Mendeleev's Periodic Table. Interestingly, Mendeleev alone cannot be credited for conceiving the idea of periodic properties of the elements; it simultaneously came to the mind of many scientists. Eric Scerri, an expert in the history of science, particularly the history of chemistry, described the discovery of the Periodic Table as a case of "simultaneous discovery", or a collective phenomenon involving many individuals (Scerri 2015).

The 1860 Karlsruhe Congress, the first international chemistry conference, was the indirect inspiration or source of the idea of a periodic system of elements. However, the similarities between chemical elements were observed by many scientists for a long time earlier. For example, in 1827, German chemist Döbereiner started to work on chemical periodicity. He proposed "triads of elements", three elements of similar properties, with the middle element's atomic weight (AW) approximately the average of those of the other two (e.g. Li, AW = 7; Na, AW = 23; K, AW = 39). But he could not group many known elements at that time by this series.

The Karlsruhe Congress was organized mainly on the initiative of Kekulé along with two colleagues. At the time of the Congress, Dalton's atomic theory (i.e. atoms are the smallest building blocks of chemical compounds) was widely accepted. However, there was much confusion about the relative atomic weights of the elements. The Congress was called to settle the confusion regarding the concepts of "atom", "molecule" and "equivalence". Well-known chemists such as Bunsen, Cannizzaro, Dmitri Mendeleev, Lothar Meyer, and many more attended the Congress. The gathering of many chemists had a catalytic effect on the development of the periodic system of elements. According to Lothar Meyer, "the congress was very useful, and undoubtedly helped to a large extent in the development of the periodic system of the elements". Mendeleev wrote, "the meeting produced a remarkable effect on the history of our science that I consider it a duty … to describe all the sessions ….". Alan Rocke, a historian of chemistry at Case Western Reserve University, USA, described the 1860 Karlsruhe meeting thus: "the result of the conference—the Periodic Table—came to fruition" (Mönnich 2010; Evert 2010). In the Karlsruhe Congress, an accurate list of atomic masses was made available by famous Italian chemist Cannizzaro, which was the key factor behind the discovery of the Periodic Table. In fact, at least six scientists from different countries, with different languages, came with the idea of the Periodic Table over a span of nine years!

The first significant advance towards the periodic system of the elements was published in 1862 by a French geology professor, Alexandre Béguyer de Chancourtois. The three-dimensional arrangement of

Figure 1. Timeline of the discovery of a few chemical elements.

the periodicity of elements presented by him is known as "telluric screw". In this arrangement, the atomic weights of the elements were plotted on the outside of a cylinder. One complete turn corresponded to an atomic-weight increase of 16, and the element obtained after the complete turn of the cylinder was similar to the element before turning the cylinder. The telluric screw did not explain the similar properties of all the elements known at that time. Nevertheless, it was the first attempt to develop the Periodic Table.

John Alexander Newlands, a British chemist, was the first person to arrange the elements in the order of their masses and ultimately published the Periodic Table in 1865. Newlands's Periodic Table (Figure 2) is based on the "law of octaves", according to which every eighth element in the table is similar to the corresponding first element. Newlands arranged the then known elements into seven groups with eight rows in his table. Unfortunately, the society and the peer community were not ready to accept the periodic properties of chemical elements at that time. His contribution was recognized much later, when, in 1887, The Royal Society conferred the Davy Medal on him.

There are at least two forgotten heroes who formulated the Periodic Table in their own way—keeping the central theme the same, periodicity of elements is dependent on their relative atomic mass. William Odling, FRS, professor at Oxford and an English chemist, published a Periodic Table with 57 known elements in 1864 (in 1864 Newlands had included only 24 elements). Odling was one of the attendees at the Karlsruhe Congress and was a great follower of Cannizzaro. Unfortunately, Odling failed to convince the chemist community about his Periodic Table and possibly under frustration he gave up this mere classification of the elements and concentrated on more fundamental science, by his own judgement (Scerri 2015).

An unconventional and unique periodic chart of the elements was published in 1867 by a German-American scientist, Gustavus Hinrichs, professor of natural philosophy, chemistry and modern languages at the University of Iowa in the US (Wikipedia 1). The word "unique" can be applied to Hinrichs in multiple ways. Wisdom and thinking on a periodic system of the elements was mainly concentrated in Europe. Hinrichs in that sense is the first one outside Europe who joined this school. Moreover, he is probably the only one who arranged the system in a circular way and included similar elements in a group in the form of spokes on a bicycle wheel (Scerri 2013). The elemental groups described by Hinrichs were highly rational. For example, he correctly placed Cu, Ag and Au in one group; even Mendeleev neglected this aspect in his earliest table of 1869.

It would be nice if we could refer to Mendeleev's Periodic Table with the prefix "finally": "Finally, Mendeleev published his Periodic Table correcting all the shortcomings of other Periodic Tables", and so on. But it did not happen. One German chemist, Lothar Meyer, published his Periodic Table in 1870, only a few months after Mendeleev published his first version of the Periodic Table. Both Mendeleev and Lothar Meyer were unaware of each other's work though both of them were students of Bunsen. The peer community gave credit to both Lothar Meyer and Dmitri Mendeleev for conceiving the idea of the Periodic Table. Both of them were awarded the Davy Medal of the Royal Society (London) in 1882 "for their discovery of the periodic relations of the atomic weights".

The world celebrated 150 years of Mendeleev's Periodic Table, despite the fact that Mendeleev (in Russian Dmitry Ivanovich Mendeleyev) has not discovered a single element. All he did was to make a table and put the elements in the small squares of the table. Mendeleev took nine years from the Karlsruhe Congress to publish the first Periodic Table in 1869

H	**Li**	**Ga**	**B**	**C**	**N**	**O**
F	**Na**	**Mg**	**Al**	**Si**	**P**	**S**
Cl	**K**	**Ca**	**Cr**	**Ti**	**Mn**	**Fe**
Co, Ni	**Cu**	**Zn**	**Y**	**In**	**As**	**Se**
Br	**Rb**	**Sr**	**Ce, La**	**Zr**	**Dy, Mo**	**Ro, Ru**
Pd	**Ag**	**Cd**	**U**	**Sn**	**Sb**	**Te**
I	**Cs**	**Ba, V**	**Ta**	**W**	**Nb**	**Au**
Pt, Ir	**Tl**	**Pb**	**Th**	**Hg**	**Bi**	**Th**

Figure 2. Newlands's Periodic Table, 1866.

(Figure 3). But by that time, many versions of the Periodic Table had been published by many scientists. The basis of earlier Periodic Tables was the relative atomic mass, what Cannizzaro provided on the last day of the Karlsruhe Congress. Mendeleev's Periodic Table, which he named "Periodic Table of the Chemical Elements", was also based on the relative atomic mass of the elements. In 1869, he arranged all the then known 63 elements by increasing atomic weight in several columns.

In 1871, Mendeleev formulated the "law of periodicity" and published an improved version of the Periodic Table (Figure 4). Mendeleev's Periodic Table looks like a repetition of the idea conceived by his predecessors with incremental development. But it is the opposite. It is a leap in science which has covered almost all disciplines and has inspired great scientists over the years, decades and centuries since. UNESCO described Mendeleev's Periodic Table as "a unique tool, enabling scientists to predict the appearance and properties of matter on the Earth and in the rest of the Universe". In 1905, Mendeleev received the highest award of the Royal Society, the Copley Medal, "for his contributions to chemical and physical science". Mendeleev was elected a foreign member of the Royal Society, the National Academy of Sciences,

			Ti=50	Zr=90	?=180
			V=51	Nb=94	Ta=182--
			Cr=52	Mo=96	W=186
			Mn=55	Rh=104.4	Pt=197.4
			Fe=56	Ru=104.4	Ir=198
			Ni=Co=59	Pd=106.6	Os=199
H=1			Cu=63.4	Ag=108	Hg=200
	Be=9.4	Mg=24	Zn=65.2	Cd=112	
-	B=11	Al=27.4	?=68	Ur=116	Au=197?
	C=12	Si=28	?=70	Sn=118	
	N=14	P=31	As=75	Sb=122	Bi=210?
	O=16	S=32	Se=79.4	Te=128?	
	F=19	Cl=35.6	Br=80	I=127	
Li=7	Na=23	K=39	Rb=85.4	Cs=133	Tl=204
		Ca=40	Sr=87.6	Ba=137	Pb=207
		?=45	Ce=92		
		?Er=56	La=94		
		?Y=60	Di=95		
		?In=75.6	Tb=118?		

Figure 3. First Periodic Table published by Mendeleev in 1869.

	Group 1	Group II	Group III	Group IV	Group V	Group VI	Group VII	Group VIII
1	H=1							
2	Li=7	Be=9.4	B=11	C=12	N=14	O=16	F=19	
3	Na=22	Mg=24	Al=27.3	Si=28	P=31	S=32	Cl=35.5	
4	K=39	Ca=40	--=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56,Co=59, Ni=59,Cu=63
5	(Cu=63)	Zn=65	--=68	--=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Y=88	Zn=90	Nb=94	Mo=96	-=100	Ru=104,Rh=104, Pd=106, Ag=108
7	(Ag=108)	Cd=112	In=112	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Dy=138	?Ce=140	--	--	--	-- -- -- --
9	(-)	--	--	--	--	--	--	
10	--	--	?Er=178	?La=180	Ta=182	W=184	--	Os=195, Ir=197, Pt=198, Au=199
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	--	--	
12	--	--	--	Th=231	--	U=240	--	-- -- -- --

Figure 4. Periodic Table published by Mendeleev in 1871.

USA, and the Royal Swedish Academy of Sciences. The major reason for this is that Mendeleev not only classified the known elements in his table, but also indicated some blank places where then undiscovered elements could be placed along with their physical and chemical properties (Figure 5). In Mendeleev's own words: "We must expect the discovery of many yet unknown elements—for example, elements analogous to aluminium and silicon—whose atomic weights would be between 65 and 75." Had he not indicated the undiscovered elements with correct relative atomic weights, then his Periodic Table would not at all have received any additional attention. Instead, today Mendeleev's Periodic Table is one of the wonders of science. He was not awarded Nobel Prize (though he was nominated twice, in 1906 and 1907), but celebrity scientists have received the Nobel Prize by filling in the gaps or the blanks in Mendeleev's Periodic Table. Only a few all-time great scientists have secured a place in the Periodic Table, Mendeleev is one of them. His name is in the same row with Curie, Einstein, Fermi and Lawrence.

The elements discovered after the publication of Mendeleev's Periodic Table are shown in Figure 6. A careful look at Figure 6 will help one to classify the timeline of the discovery of the elements after the first publication of the Periodic Table: (i) 1869–1898: 15 elements were discovered. These discoveries can be designated as "Mendeleev inspired" or inspired by the prediction of elements in Mendeleev's Periodic Table. (ii) 1898–1905: 1898 is the most remarkable year in the history of science, radioactivity was discovered. Simultaneously two elements, radium and polonium, took place in the Periodic Table. Inspired by Curies, ^{227}Ac was discovered in pitchblende, ^{222}Rn and ^{234}Pa were discovered from radium and uranium decay chain respectively. (iii) British physicist Henry Moseley changed the concept of periodicity of elements. According to him periodicity is dependent on atomic number not on atomic mass. Mendeleev's Periodic Table was promoted to the modern Periodic Table with this new concept. Henry Moseley predicted two stable elements still to be discovered. The discovery of Hf and Re between 1923–25 can be definitely viewed as Moseley inspired discovery (iv) The discovery of rest of the elements, Fr, Tc, At, Pm, all trans-uranium actinides (except Es and Fm) and all trans-actinides elements were discovered by charged particle or neutron-induced reactions in accelerators or reactors. Frédéric Joliot and Iréne Curie paved the way for artificial transmutation (v) Interestingly two elements Es and Fm were discovered in the debris of the first hydrogen bomb fall out. In Table 1, the discovery of post-Mendeleev elements have been classified.

The evolution of Mendeleev's Periodic Table to today's Periodic Table is an exciting story of evolution of science, technology, humanity, scientific frustration and ambition, and above all, the story of great people. The history of discovery of each element is the

Figure 5. Chemicals used by Mendeleev kept in the Chemistry Department, St. Petersburg University, Russia. Inset at left: Gallery where Mendeleev addressed his students. Inset at right: Mendeleev's classroom (Photo: S. L.).

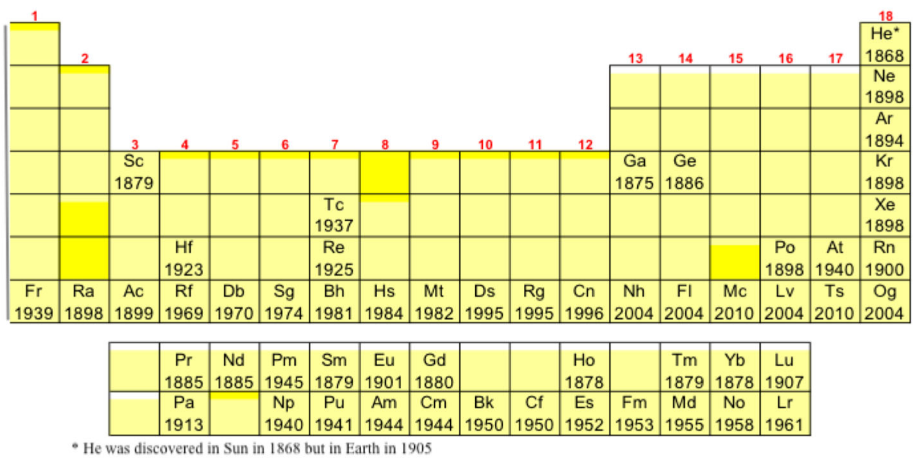

Figure 6. The elements discovered after Mendeleev published his first Periodic Table.

Table 1. Various stages of discovery of post-Mendeleev elements.

Period	Elements discovered
1869–1898: *Mendeleev inspired*	Sc, Ga, Ge, Ne, Ar, Kr, Xe, Pr, Nd, Sm, Gd, Ho, Tm, Yb, Eu
1898–1905: *Marie Curie inspired*	Ra, Po, Ac Rn, Pa
1923–1925: *Moseley inspired*	Hf, Re
1937–2010: *Frederic Joliot and Irene Curie inspired*	Fr, Tc, At, Pm, Np, Pu, Am, Cm, Bk, Cf, Md, No, Lr, Rf, Db, Sg, Bh, Hs, Mt, Ds, Rg, Cn, Nh, Fl, Mc, Lv, Ts, Og
1952–1953: *Bomb product*	Es, Fm

history of scientific perfection, patience and hard work. It is impossible to depict each discovery in the limited pages of the journal. Only some selected historical aspects have been summarized here to give readers the essence of the Periodic Table—a show of excellence.

2. Filling the gaps: 1869–98

The nitrogen density puzzle: Lord Rayleigh, an English physicist, was working on the accurate re-determination of the density of different gases present in air. After working with oxygen, his attention turned to nitrogen. He isolated nitrogen gas from the air, using a method suggested by his friend—another British chemist—Sir William Ramsay. Lord Rayleigh took a series of data and just before disposing his work on the density measurement of nitrogen, he thought to repeat the experiment. But this time, nitrogen would be prepared directly from ammonia, not from air. He again obtained a series of valuable observations but surprisingly the density of nitrogen was less than what was observed in the previous method. The difference was small in magnitude, one part in thousand. This small difference is generally ignored in any experiment, or the average result is reported or at the best reported as uncertainty of the experiment. But Lord Rayleigh was confident that it was not an experimental error. The density of nitrogen obtained from air is slightly higher than it is obtained from ammonia. The two alternative explanations of the discrepancy might be: (i) the atmosphere derived nitrogen contains a heavier gas, hitherto unknown or (ii) the ammonia derived nitrogen is in a dissociated state. His friend and colleague William Ramsay was in favour of the first explanation. The dissociated state of nitrogen may be unstable. Therefore, Rayleigh kept the nitrogen sample for eight months, and repeated the experiment. The result was the same. The nitrogen derived from ammonia was slightly lighter than the atmospheric nitrogen.

The next task was to identify the unknown heavier gas in atmospheric nitrogen. The task was carried out by Ramsay and Rayleigh, initially independently, and later in concert. Both of them adopted multiple methods in search of this unknown gas. One of the methods is schematically presented in Figure 7.

The inertness towards any chemical reaction is the striking property of the newly discovered gas. Lord Rayleigh continued his research with the physical properties of this gas. The 1904 Nobel Prize in Physics was awarded to Lord Rayleigh for his investigations of the densities of the important gases and for his discovery of argon, a component of air, which was undiscovered till Rayleigh and Ramsay's experiment.

Side by side, his colleague Ramsay's attention was drawn to some unknown spectral lines, that came out from a gas obtained when uranium containing ores were heated with dilute sulfuric acid. At first, Ramsay thought that this gas was argon. Careful observation of this spectrum lines revealed its resemblance with the reference line, which had been first observed in the solar spectrum during an eclipse of the sun in 1868 in India. Shortly after due deliberation, it was established that the new line is of a new element, "helium". It has been found that from the specific heat data (ratio of specific heat at constant volume to that of constant pressure) that the helium, like argon, is also monoatomic in nature and it is equally inert like argon. Therefore, the discovery of helium and argon led to establishing the family of inert gas elements.

Looking at the Periodic Table, Sir Ramsay had a feeling that there must be at least three other elements in the series. He and his assistant collected and investigated the gases evolved from numerous minerals kept at the British Museum, various British and Scottish mineral springs, meteorites, etc. They even made an expedition to the spa village of Pyrenees in France to collect the gases from the hot springs. A series of fractional distillation of all the gases collected from different parts of the world resulted in mere frustration. Only some of the collected fraction showed spectral lines of helium and argon, those already discovered.

The entire years 1896 and 1897 were spent on collecting 15 litres of argon gas. From this 15 litre

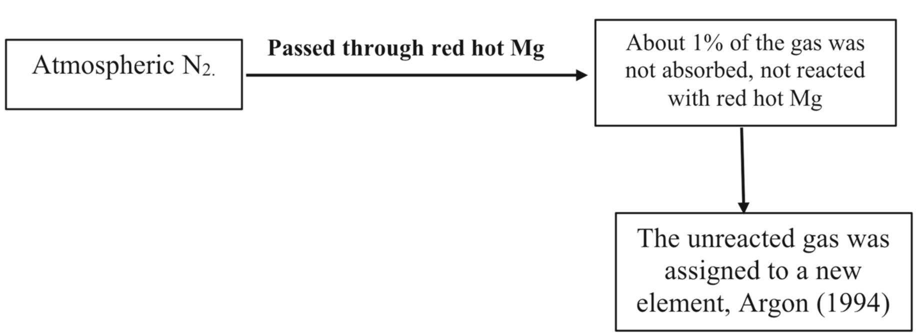

Figure 7. A simple pictorial presentation of argon discovery.

fraction, after concentrating the gas, they were able to find the new spectral line of a new element, krypton (the hidden one). The gas was forty times heavier than hydrogen, implying the atomic weight 80. On June 1898, the team of Ramsay announced another new gas, that has a lower boiling point than argon and named the element as neon. In September 1898, another new gas was discovered, by liquefying air, and fractionation of its components like argon, krypton, etc. The gas was named 'xenon' or the 'stranger'.

The group measured the ratio of the specific heats, refractivity, densities, compressibility and the vapour pressures of all these gases. From all these observations, they concluded that helium, neon, argon, krypton, and xenon are monatomic. In general terms, they concluded that these gases show a regular trend in their properties, and they fill the gaps in the Periodic Table.

A quote from the Nobel lecture of Ramsay will help to understand the colossal task, the tasks that he carried out to discover and measure the physical parameters of these inert gases: "Amounts of neon and helium in air have since been measured; the former is contained in air in the proportion of 1 volume in 81,000; the latter, 1 volume in 245,000; the amounts of krypton and xenon are very much smaller – not more than 1 part of krypton by volume can be separated from 20,000,000, of air; and the amount of xenon in air by volume is not more than 1 part in 170,000,000".

The difficulty of discovery was not only the presence of these gases in minuscule amount, but one has to imagine that there was no existence of a single member of this inert gas family. Even Mendeleev's prediction excluded these elements. Sir Ramsay has to reconstruct the mental picture of the Periodic Table and successfully discover all the elements.

Sir William Ramsay was awarded the Nobel Prize in 1904 "in recognition of his services in the discovery of the inert gaseous elements in air, and for determination of their place in the periodic system."

3. Filling the gaps: 1898–1905, Marie Curie inspired

The next part of the story has been told millions of times by millions of people in millions of context. However, the story of the discoveries by the Curies is once again important in the context of development of the Periodic Table.

In November 1895, Wilhelm Röntgen discovered X-rays—the discovery that conferred the greatest benefit to humankind. Immediately, the scientific community showed unprecedented enthusiasm in Röntgen's discovery. Just three months after, the French physicist Henri Becquerel discovered radioactivity. By the time, a young Polish lady, Marie Sklodowska, joined Professor Pierre Curie's laboratory in Paris. Marie decided to work on uranic rays for her doctoral degree. The properties of uranic rays were till that time only qualitative. Curies wanted to measure radioactivity quantitatively by using the property of ionization of air by uranic ray. She undertook the study on the radiation of uranium compounds, and extended this study to other substances, including thorium compounds. It was found that the activity of a compound is directly proportional to the amount of uranium or thorium present in the compound (Figure 8).

The important conclusion of Marie Curie's Ph.D. thesis, defended in June 1903, is that the radioactivity is an atomic property, which implies that the atom is no more indivisible, and therefore, it is a milestone in fundamental physics. Madame Curie along with her husband Pierre Curie received the Nobel Prize (shared with Henry Becquerel) for this path-breaking discovery in physics.

The Curie couple had some unexpected observations for some minerals, like pitchblende or chalcolite. These minerals showed much greater activity than what was expected, from the stoichiometric composition of uranium present in the ore. To get rid of this puzzle, Marie prepared synthetic chalcolite (crystallized phosphate of copper and uranium) from pure products, and the measured activity of this synthetic product was consistent with the uranium content. The Curie couple assigned the high activity of natural pitchblende again to another hitherto unknown element which has much higher radioactivity compared to uranium. To prove the concept, Marie and Pierre Curie, the all-time great physicists, started the painstaking pure classical chemistry experiments in a makeshift laboratory (Figure 9). Madame Curie continued the experiment alone after the untimely demise of Pierre Curie in 1906. Finally, in 1910, Madame Curie could isolate a few milligrams Ra from tons of pitchblende, and determine its atomic weight accurately for which she received the second Nobel Prize. The entire work of Marie and Pierre Curie from 1898 to 1910 should be viewed in one string. Figure 10 and Figure 11 presents schematically Curies's experiment, and how they discovered polonium and radium. Each step of this chemical separation was repeated innumerable times and the radioactivity present in each fraction was measured after each step of chemical separation.

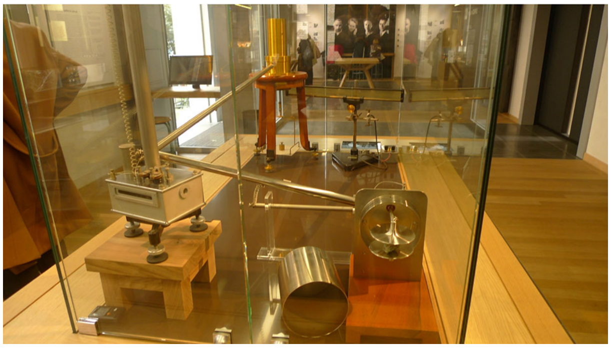

Figure 8. The electrometer which the Curies used to measure radioactivity by ionizing the gases with the emitted radioactivity. The instrument is kept at the Musée Curie, Paris, France (Photo: S.L.).

To discover the two elements Po and Ra, to fill in just two squares of the Periodic Table, Madame Curie handled a huge amount of radioactivity, and as a result succumbed to aplastic anaemia, caused due to prolonged exposure to radiation. This history of the Periodic Table is also the history of highest level of humanity and sacrifice.

In 1900, Friedrich Ernst Dorn, a Germany physicist, reported that a gas is emitted from thorium and radium compounds, which is radioactive. He named this gas as "radium emanation". "Radium emanation" became a popular term to describe the biological effects of radium. In the early 1900s, radium was inhaled to treat lung cancer, and it was believed that radium emanation was actually responsible for killing cancerous cells (Saudermann 1911). Ernest Rutherford became interested in characterizing radium emanation. He proposed two possibilities, either (i) this gas is fine dust particles of the radioactive substances or (ii) a vapour from thorium compounds. It was easily proved experimentally that the emanation was not dust. Therefore, Rutherford concluded that the 'radium emanation' was vapour of thorium. Within a year, Rutherford changed his view and was in favour of the third possibility that the gas is a hitherto unknown new element. They had estimated a rough value of the atomic weight of the gas which was far less than thorium or radium. So radium emanation was first identified by Rutherford as a new element (afterwards named as radon). Therefore, Rutherford is the true discoverer of radon (Rayner-Canham and Rayner-Canham 2004). Later, Ramsay and his co-worker isolated radon and determined its density, and radon became the heaviest of all known gases. At the same time, it was inert to chemical reactions. Rn was accommodated as the heaviest member of the inert gases. Interestingly Rutherford himself gave the credit of discovery to Curies. Nevertheless, the discovery of Rn gave the concept of half-life, α decay and β decay, etc. All these helped Rutherford investigate into the disintegration of elements, for which he was awarded the Nobel Prize in Chemistry in 1908.

Protactinium was first identified in 1913 by K. Fajans and O. Göhring during the study of ^{238}U decay chain. In the year 1917/18, two groups, Otto Hahn and Lìse Meitner from Germany and F. Soddy from Great Britain, independently discovered another long-lived isotope of protactinium in ^{235}U chain (Wikipedia 2). Figure 12 and Figure 13 show the respective protactinium isotopes in ^{238}U and ^{235}U decay series.

4. Moseley: Transition of Mendeleev's Periodic Table to modern Periodic Table

Rutherford proved by his famous experiments on the scattering of α-particle on gold foil that the mass of the atoms are concentrated in the nucleus which is positively charged and surrounded by negatively charged electrons to make an atom electrically neutral.

Figure 9. Madame Curie's laboratory (Musée Curie, Paris, France). Everything is kept unchanged except the table top – which was contaminated with huge amount of radioactivity, therefore, changed (Photo courtesy: S. L.).

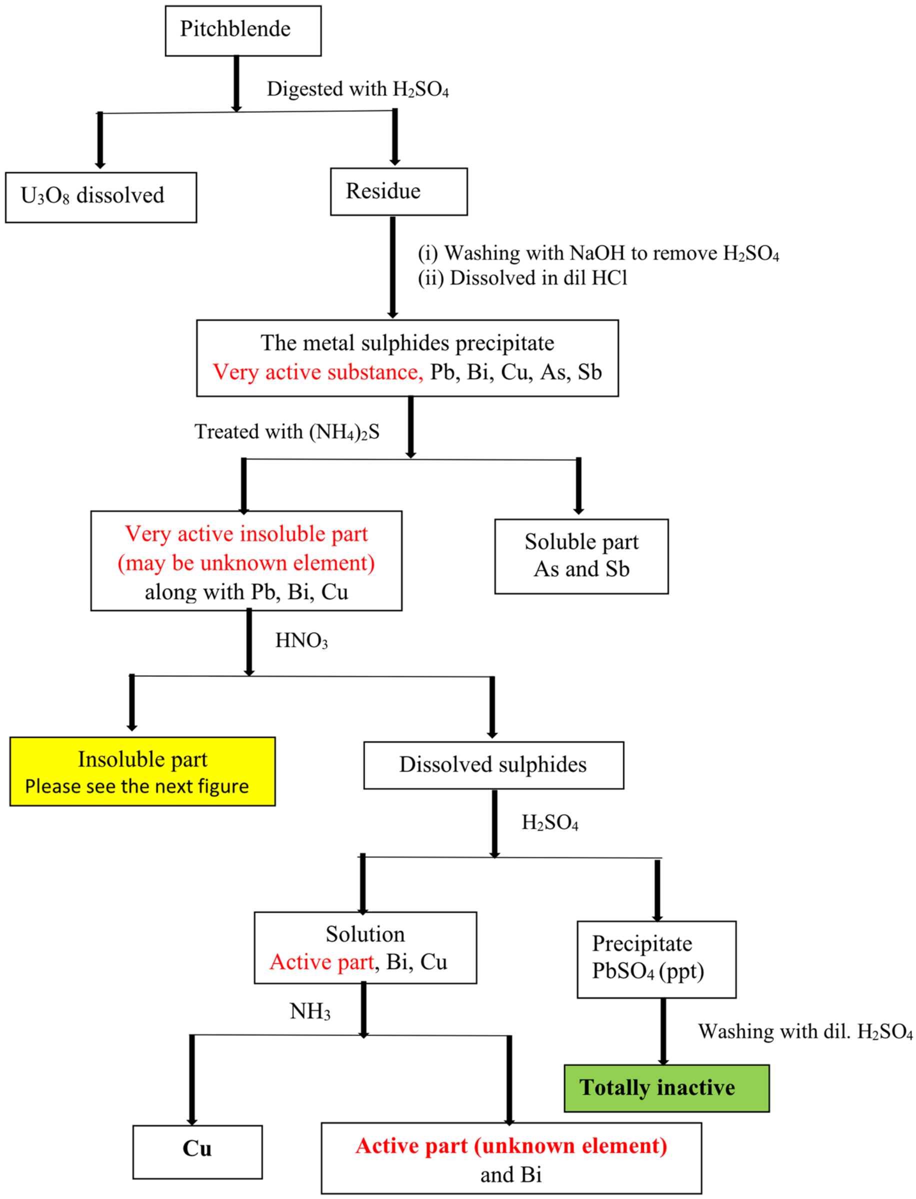

Figure 10. The first part of Curies' experiment. They failed to separate the active substance from bismuth. They wrote in their diary (1998) "we obtained a substance whose activity is about 400 times greater than that of uranium. If the existence of this new metal is confirmed, we propose to call it polonium from the name of the country of origin of one of us."

He also determined the number of positive charges on the nucleus of gold and some other elements by α-scattering experiments and noticed that the experimentally determined charges are approximately half of the atomic weight of the elements. Hence Rutherford concluded that the atomic weight should have a relation with the positive charge in the nucleus and usually higher is the atomic weight, higher is the positive charge. He discussed this hypothesis with a new student, Henry Moseley who wanted to do Ph.D. under his supervision and assigned him the job of verification of this hypothesis by suitable experiments. As the results of determining the positive charge of the nucleus by α-scattering experiments were not very accurate, Moseley looked for other means. At that time it was known that X-rays, produced in the Crookes tube, are of two types: the continuous part due to slowing down/stoppage of electrons and is featureless, and the few peaks having very high intensity depending upon the metal used in the anti-cathode. Moseley decided to take the photographs of these peaks that appeared in X-rays for different

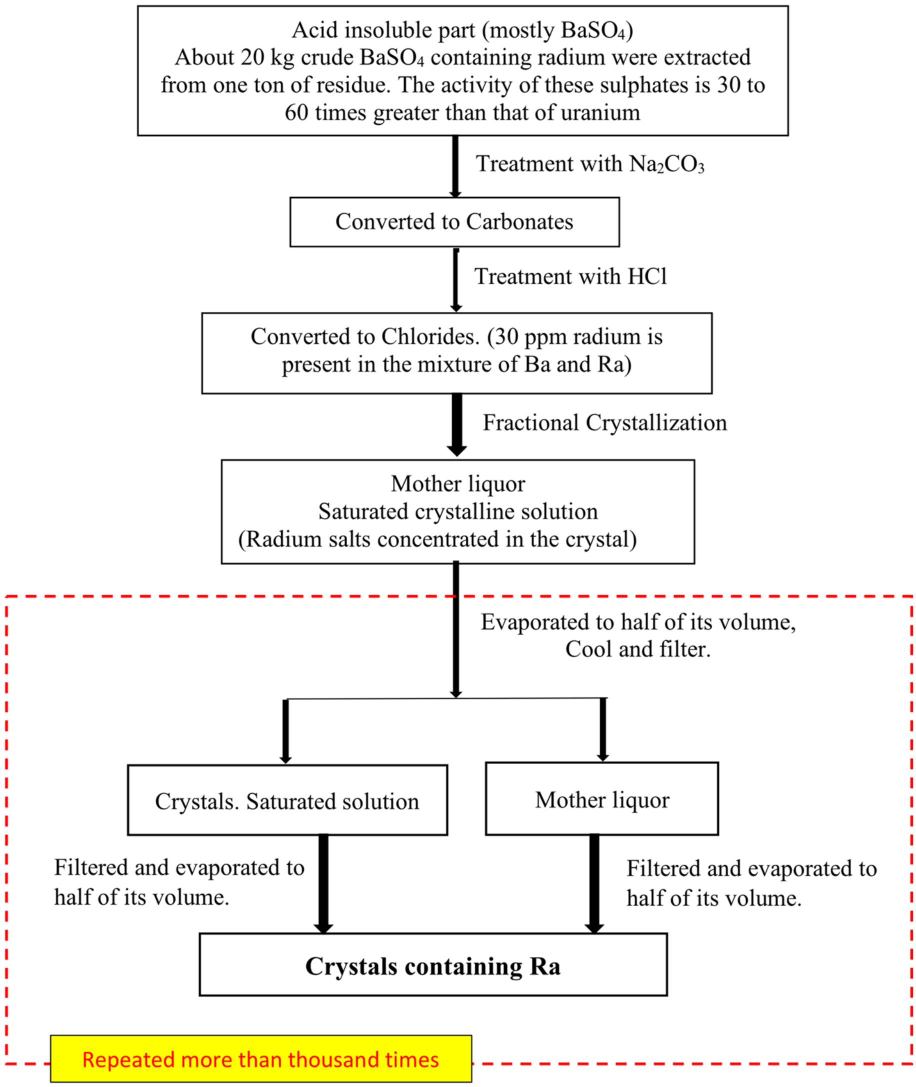

Figure 11. Schematic presentation of Madame Curie's experiment for isolation of milligram amount of radium from tons of pitchblende. The Nobel Prize was conferred to her in 1911 for isolation of radium metal, this being the first time that the distinction had been conferred upon a previous prize winner.

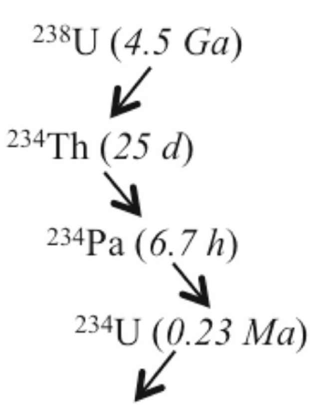

Figure 12. Short-lived ^{234}Pa (6.7 h) is a part of ^{238}U decay series.

elements and compared them to see if these peaks are related to the positive charge of the nucleus. By perfecting the photographic methods, he could determine the frequency of the emitted X-ray very precisely.

He started with an anticathode made of aluminium and examined the X-ray spectra of thirty-eight elements—from aluminium to gold. He made the following observations:

(I) X-rays of different elements are different.
(II) The heavier the element, the shorter is the wavelength and higher is the penetrating power of the emitted X-ray.
(III) When the numbers of the elements, representing their position in Mendeleev's table is

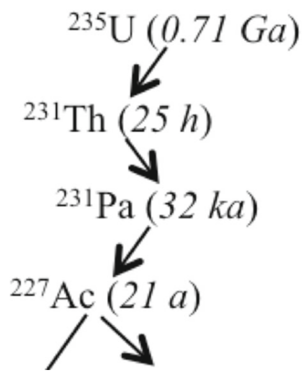

Figure 13. Long-lived ^{231}Pa (32 ka) is a part of ^{235}U decay series.

plotted with the inverse of the square roots of the vibration frequencies of their X-rays, a straight line is obtained.

(IV) He concluded "There is in the atom a fundamental quantity which increases by regular steps as we pass from each element to the next. This quantity can only be the charge on the central positive nucleus."

With these observations, in 1912, Moseley at his 25 years of age, discovered that the positive charge in the nucleus, i.e. the atomic numbers of the elements are more fundamental than atomic weight—a breakthrough fundamental discovery in science. He prepared a new table on the basis of atomic numbers. At that time the known element with the highest atomic number, 92, was uranium. So from his table, it became obvious that no more than 92 elements from hydrogen (atomic number 1) to uranium (atomic number 92) can be accommodated. His discovery also helped the proper placing of the elements which was considered anomalous in Mendeleev's Periodic Table. For example he determined that the atomic number of potassium to be 19 and figured out that it should be placed before argon although their atomic weights are in reverse order. Similarly, he corrected the positions of cobalt and nickel, and iodine and tellurium. In the Mendeleev's Periodic Table, positions of the "rare earth" were rather baffling. In Moseley's Table, these 15 elements could be fitted unambiguously with the atomic numbers from 57 to 71. In this context, after the untimely death of Moseley, the quote of the French scientist, Georges Urbain of the University of Paris (who did remarkable work on the separation and identification of "rare earth" elements) is worthy to mention, "I had been very much surprised when I visited him at Oxford to find such a very young man capable of accomplishing such a remarkable piece of work. The law of Moseley confirmed in a few days the conclusions of my efforts of twenty years of patient work." Arrhenius in 1915 nominated him for Nobel Prize in Chemistry as well as in Physics. But in the same year (1915) he died in war at his 27 years of age.

5. Filling the gaps: 1923–1925, Moseley inspired

In Moseley's Table, there were rooms for elements with atomic numbers of 43, 61, 72, 75, which were unknown at that time (Figure 14). In 1914, the element 72, laid vacant by Moseley and also predicted by Mendeleev was reported as one of the rare earth elements. But Niels Bohr was much disturbed by this claim, because it was contradictory to his proposal on the electronic structure of an atom. The f-orbital can accommodate only 14 electrons, so there is no place to accommodate another rare earth element. He instructed his colleagues George von Hevesy and Dirk Coster at the University of Copenhagen to search for the missing element predicted by Moseley in Zr ores, as it would resemble zirconium. Finally, in 1923, element 72, was discovered by George von Hevesy and Dirk Coster. To honour Niels Bohr, the element was named as hafnium—Hafnia is the old name of Copenhagen, the birth place of Niels Bohr. Discovery of rhenium, element 75, was announced by Walter Noddack and Ida Tacke of Berlin in 1925.

6. Frédéric Joliot-Curie and Irène Curie

They have not discovered any new element. But the history of the Periodic Table would be incomplete if the contributions of Frédéric and Irène Curie are not discussed. In February 1934, Frédéric Joliot and Irène Curie published a half of a page paper in *Nature* wherein they claimed the first artificial transmutation and production of new positron-emitting radioisotope ^{13}N produced by the α-induced reaction on boron ($^{10}B + {}^{4}He = {}^{13}N + n$) (Joliot and Curie 1934). Similarly, they also produced ^{30}P and ^{27}Si by the nuclear reactions—$^{27}Al + {}^{4}He = {}^{30}P + n$ and $^{24}Mg + {}^{4}He = {}^{27}Si + n$ respectively. They were awarded the Nobel Prize in 1935 in Chemistry "in recognition of their synthesis of new radioactive elements". Irène and Frédéric's discovery not only conferred the greatest benefit to humankind by paving the way for the production of radioisotopes for clinical use, it also opened

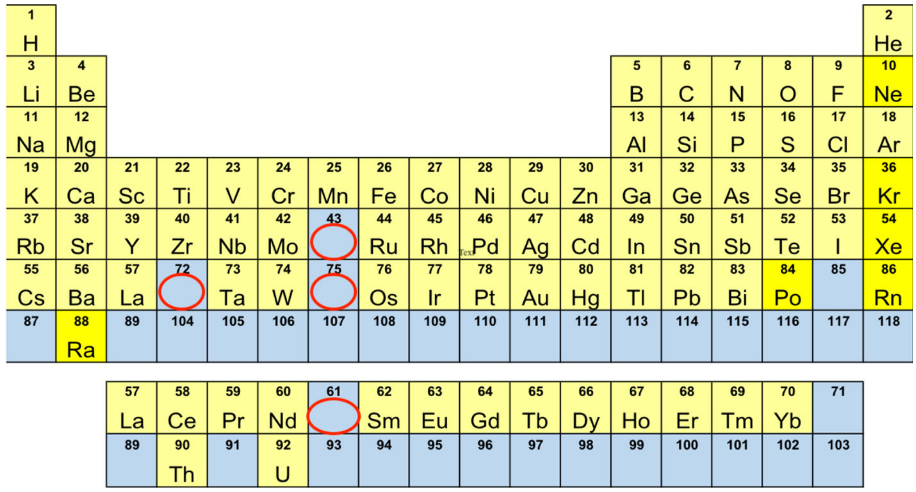

Figure 14. The Periodic Table after Moseley in 1914 (incorporated in the modern ACS Periodic Table by the author). The four red marks indicate the four elements "to be discovered" predicted by Moseley. Since Moseley worked from aluminium to gold, the elements predicted by Moseley had lower atomic number than Au.

up the possibility of synthesis of new elements and adding them to the Periodic Table. In fact, a total of 30 elements till date have been added to the Periodic Table after the discovery of cyclotron by E. O. Lawrence (Nobel Prize in Physics 1939), and the commissioning of nuclear reactor by Enrico Fermi (Nobel Prize in Physics 1938). These elements do not exist naturally on the Earth and can only be synthesized.

One of the authors (SL) cannot resist himself from narrating a personal reminiscence with Professor Pierre Joliot, son of Irène and Frédéric. When I personally met him, my very first question was, "how did your parents discover artificial radioactivity? The cross-section of $^{4}He + ^{27}Al = ^{30}P{+}n$ reaction is low, the detector technology at that time was in nascent stage, no show of cyclotron, and the alpha flux from natural source was also minimum". The comment of Professor Joliot was interesting: "not only my parents, but my grandfather and grandmother (Pierre Curie and Marie Curie) also had equal probability of being rejected by the scientific community, instead they received Nobel Prize only because their numbers were correct."

7. 1937–2010: Filling up the gaps – Frédéric Joliot and Iréne Curie inspired discovery

More than one-fourth elements (30 out of 118) of the Periodic Table are artificially produced. The artificial transmutation discovered by Frédéric Joliot and Iréne Curie paved the way for the discovery of all these elements. In 1929, E.O. Lawrence, a young faculty of physics at the University of California designed the world's first cyclotron at the age of 28. In 1937, an Italian physicist Emilio Segrè of University of Palermo, Italy, requested Lawrence for some thrown away parts of the Berkeley cyclotron. Lawrence sent him a molybdenum piece used in the cyclotron. Emilio Segrè and his co-workers noticed high radioactivity in the molybdenum foil. They radiochemically separated a new element, the first artificial element. The atomic number of the element was found to be 43. The element was named as technetium (technically produced). Segrè and his co-workers isolated ^{95m}Tc and ^{97}Tc from the molybdenum foil (probably produced by $^{95}Mo(d,2n)^{95m}Tc$ and $^{97}Mo(d,2n)^{97}Tc$ reactions). Later he visited LBNL again, and with the help of Glenn T. Seaborg separated ^{99m}Tc from molybdenum foil. The ^{99m}Tc is the magical radioisotope in nuclear medicine and annually ^{99m}Tc is administered to ten million patients for imaging purposes. The discovery of technetium was rather silent and has not received the attention of the peer community that it deserves. It is noteworthy to mention that Mendeleev predicted eka-manganese with atomic weight 100, even in his 1871 version of Periodic Table (Figure 4). About 65 years after, the discovery of technetium proved the greatness of Mendeleev's prediction. In 1914, Moseley also predicted the element number 43 (see Figure 14).

In Moseley's table, element 85 was empty, Mendeleev also predicted eka-iodine. Niels Bohr's electronic theory also suggested that heaviest halogen is yet to be discovered. All these again inspired Emilio Segrè and his colleagues Dale Corson and Kenneth

Mackenzie to search for the heaviest halogen with the Berkley cyclotron. They discovered ^{211}At in 1940 by bombarding bismuth with alpha particle (^{209}Bi + ^{4}He = ^{211}At +2n). Till date about 22 isotopes of At have been discovered, none of them are stable and the longest living isotope of astatine is ^{210}At ($T_{1/2}$ = 8.1 h). ^{211}At is an alpha emitter and till date it is the most promising radionuclide for targeted alpha therapy. Emilio Segrè was a celebrity physicist; his life was full of discoveries. He discovered two elements technetium and astatine which are serving humankind. He was also the discoverer of slow neutron with Enrico Fermi, but his most fundamental discovery was antiproton, for which he was awarded the Nobel Prize in Physics in 1959.

Mendeleev indicated a "-" dash after uranium indicating an unknown element beyond uranium. In the 1940s, Enrico Fermi had already discovered slow neutrons. He bombarded uranium with these slow neutrons. ^{238}U captured the slow neutron and converted to ^{239}U. Fermi believed that he had synthesised a new element which has been formed by the β decay of ^{239}U. Therefore, he reported the first man-made transuranic element with atomic number 93. For this, he was awarded the Nobel Prize in 1938. In the meantime, in 1939, Otto Hahn, Fritz Strassmann, and Lise Meitner discovered fission. Soon it was realized that Enrico Fermi had actually observed a lighter element caused by the fission of uranium and had not discovered element number 93.

Just two years after, in 1940, after several unsuccessful experiments, Edwin McMillan at the Berkeley Radiation Laboratory, could synthesis element number 93 by irradiating uranium target with a slow neutron, using the same nuclear reaction, $^{238}\mathrm{U} + \mathrm{n} \rightarrow {}^{239}\mathrm{U}(\beta)\ {}^{239}\mathrm{Np}$. After the Fermi incident, Edwin McMillan was careful and a series of painstaking chemistry experiments confirmed the new element with atomic number 93, which was later named as neptunium.

From the end of 1940, Seaborg era started in Berkeley Radiation Laboratory. Glenn T. Seaborg, a 28 years old young nuclear chemist, bombarded uranium with deuteron. He along with colleagues, Edwin McMillan, Emilio Segrè and Joseph Kennedy, identified and chemically isolated another new trans-uranium element plutonium with atomic number 94, which has been produced via $^{238}\mathrm{U} + {}^{2}\mathrm{H} \rightarrow {}^{238}\mathrm{Np}(\beta){}^{238}\mathrm{Pu}$ reaction. In the meantime, in 1944, Seaborg has published his famous actinide theory. Now the numbers of actinides are fixed. The rest is history. Glenn T. Seaborg at Lawrence Berkeley National Laboratory (LBNL) along with his colleagues like Albert Ghiorso synthesized Am, Cm, Bk, Cf in series.

[1940]: (^{238}U + ^{2}H) ^{238}Np (β)^{238}Pu (88 a)
[1945]: (^{239}Pu + n) ^{240}Pu(+n) ^{241}Pu (β)^{241}Am (432.2 a)
[1944]: (^{239}Pu + ^{4}He) ^{242}Cm (160 d)
[1949]: (^{241}Am + ^{4}He) ^{243}Bk (4.5 h)
[1950]: (^{242}Cm + ^{4}He) ^{245}Cf (45 m)

Mendeleev put 5 dashes after uranium. Therefore, the synthesis of californium was for the first time, beyond the imagination of Mendeleev. The Nobel Prize in Chemistry in 1951 was awarded to Edwin McMillan and Glenn Theodore Seaborg "for their discoveries in the chemistry of the transuranium elements".

The history of the Periodic Table is the history of society, humanity, patience, hard work, and sometimes frustration. Even war had a role in the development of Periodic Table. Ivy Mike, the first thermonuclear bomb was detonated on November 1, 1952. The debris of the bomb was analysed by Albert Ghiorso and his team in LBNL, and to their surprise, they found two new elements, the atomic numbers were determined and found to be 99 and 100, afterwards named as einsteinium (Es) and fermium (Fm). The power of this bomb was equivalent to 10 megatons TNT. The tremendous energy generated from the bomb, made it possible for the following unusual reaction. Afterwards, different isotopes of Es and Fm were synthesized by accelerator induced reactions.

$$\left({}^{238}\mathrm{U}+15\mathrm{n}\right)(6\beta)^{253}\mathrm{Cf}(\beta)^{253}\mathrm{Es}(20.47\ \mathrm{d})$$
$$\left({}^{238}\mathrm{U}+15\mathrm{n}\right)(6\beta)^{253}\mathrm{Cf}(\beta)^{253}\mathrm{Es}(\beta)^{253}\mathrm{Fm}(3\ \mathrm{d})$$

The element number 101 was produced in LBNL under the leadership of G. T. Seaborg and Albert Ghiorso using following nuclear reaction:

$$[1955]:\ \left({}^{253}\mathrm{Es}+{}^{4}\mathrm{He}\right)^{256}\mathrm{Md}(1.17\ \mathrm{h})$$

None but G. T. Seaborg proposed the name of element number 101 as mendelevium. In the time of cold war, it was not very easy to convince the US bureaucrats to give a Russian name to a newly discovered element. By doing that Seaborg proved again that science has no boundary. At last the creator secured a position in the Periodic Table.

Synthesis of nobelium (atomic number 102) was first attempted in Stockholm 1957 using the reaction $^{244}Cm + {}^{13}C$. Later, it was found that their claim cannot be true. Simultaneously, experiments were carried out at Berkeley and Dubna. Albert Ghiorso performed the experiment at LBNL by bombarding $^{244,246}Cm$ by ^{12}C and they obtained 3 s half-life, which was assigned to ^{254}No. Later, FLNR studied various C + Cm reactions and showed that ^{254}No has half-life ∼55 s, and that the 3 s is from ^{252}No. LBNL repeated the experiment and confirmed that Dubna was correct. Therefore, nobelium was discovered by both LBNL and Dubna. This example shows that research with heavier elements became difficult due to the short half-life of the product, and also the yield in such nuclear reactions is too low.

The last actinide lawrencium (atomic number 103) was discovered in LBNL by Ghiorso, Sikkeland, Larsh and Latimer using the following nuclear reaction.

$$[1961]: \left(^{252}\mathrm{Cf} + {}^{11}\mathrm{B}\right)^{263}\mathrm{Lr}(10\ \mathrm{h})$$

8. Journey to the Terra Incognita

The last element of the actinide series, Lr, was discovered in 1961. What is next? Is it possible to synthesize an element after Lr? By the time, few more centers like Gesellschaft für Schwerionenforschung, GSI, Germany and RIKEN, Japan also started research on the heaviest elements. Exploration of these transactinide elements is a very difficult task. Their synthesis—even just one atom—is a challenge. Albert Ghiorso and his group (Nurmia, Harris, Eskola and Eskol) successively reported the synthesis of elements 104, 105, 106 using the following nuclear reactions.

[1969]: $^{249}Cf(^{12,13}C,xn)\ ^{257,259}_{104}Rf$ (Rutherfordium)
[1970]: $^{249}Cf(^{15}N,4n)\ ^{260}_{105}Db$ (Dubnium)
[1974]: $^{249}Cf(^{18}O,4n)\ ^{263}_{106}Sg$ (Seaborgium)

Seaborgium is the first element in the Periodic Table, which has been named to honour a living scientist G. T. Seaborg for his extraordinary credit of discovering more than 10 elements in the Periodic Table.

After synthesizing, pertinent questions were, what will be the chemical behaviour of these elements? Does Rf open the next series of d-elements? Can we place them in the Periodic Table? If yes, where? Therefore, search for a room in the Periodic Table for the newly discovered elements started. A new branch of chemistry has been developed called “atom-at-a-time chemistry” (Türler and Pershina 2013). This is because extremely low production rate of superheavy elements and their short half-life allows chemical investigation one atom at a time. The chemists wanted to place Rf and Db below Hf and Ta respectively. The essential criterion for this placement is that the two new elements must have similar chemical properties with their lower homologues, i.e., Rf should resemble the chemical behaviour of Hf and Zr, and Db should resemble Ta and Nb.

In this direction, systematic investigation on aqueous chemistry of Rf through the comparative study with the homologues Zr and Hf started at RIKEN. They pursued chloro-, fluro-, nitrate and sulphate complex formation of Rf, Hf and Zr, followed by anion-exchange or reversed-phase chromatographic extraction of these complexes. For example, they studied the displacement of the metal (M = Zr, Hf, ^{261}Rf) fluoro complexes from the binding sites of the resin by the counter anion NO_3^-. It was observed that the behaviour of ^{261}Rf was similar to their lighter homologues. In total, 3788 cycle anion exchange experiments were carried out to come to this conclusion. RIKEN also carried out a similar type of experiment with Db, Ta and Nb. All these experiments conclusively placed Rf in the same group of Zr and Hf; Db in the same group of Nb and Ta. In nutshell, chemistry played an important role in finding a place for super-heavy elements (SHE) in the Periodic Table.

Again the very important question between various superheavy groups was, “is it possible to synthesize an element beyond seaborgium?” After seven years of the discovery of Sg, Darmstadt era started for the new superheavy elements. A group of physicists like S. Hofmann, G. Münzenberg, V. Ninov, F.P. Heberger, P. Armbruster, H. Folger, etc., discovered elements number 107 to 112 in Darmstadt using the SHIP separator.

[1981]: $^{209}Bi(^{54}Cr,n)\ ^{262}_{107}Bh$ (Bohrium)
[1984]: $^{208}Pb(^{58}Fe,n)\ ^{265}_{108}Hs$ (Hassium)
[1982]: $^{209}Bi(^{58}Fe,n)\ ^{266}_{109}Mt$ (Meitnerium)
[1995]: $^{208}Pb(^{62}Ni,n)\ ^{269}_{110}Ds$ (Darmstadtium)
[1995]: $^{209}Bi(^{64}Ni,n)\ ^{272}_{111}Rg$ (Roentgenium)
[1996]: $^{208}Pb(^{70}Zn,n)\ ^{277}_{112}Cn$ (Copernicium)

The elements 107 to 112 were synthesized by cold fusion, where nuclear excitation energy is low (10–20 MeV), a stable target is used and generally, one neutron is ejected. Wherein in the hot fusion, the nuclear excitation energy is higher (30–50 MeV), a radioactive actinide target is used, and generally 3–5 neutrons are ejected.

The discovery of element number 113 (nihonium, Nh) is credited to RIKEN though Dubna also observed the element 113 as a daughter product of element 115 at the same time. RIKEN under the leadership of K. Morita produced E115 by cold fusion reaction using the following nuclear reaction.

[2004]: ^{209}Bi(^{70}Zn,n) $^{278}_{113}$Nh (Nihonium)

The first event was observed in July 2004, the second event was observed in April 2005, and the third event was observed in August 2012. This demonstrates the difficulty in SHE experiments. The two most important factors for this difficulty are extremely short half-life of the superheavy elements. The second bottleneck for SHE research is the production rate, which also became too small for heavier elements (Table 2).

Dubna again has been credited for the discovery of elements 114 to 118 under the leadership of Oganessian. Elements 114 to 118 were discovered successively using the following reactions:

[2004]: ^{244}Pu(^{48}Ca, 5n) $^{287}_{114}$Fl (Flerovium)
[2010]: ^{243}Am(^{48}Ca, 2n) $^{289}_{115}$Mc (Moscovium)
[2004]: ^{245}Cm(^{48}Ca, 2n) $^{291}_{116}$Lv (Livermorium)
[2010]: ^{249}Bk(^{48}Ca, 4n) $^{293}_{117}$Ts (Tennessine)
[2004]: ^{249}Cf(^{48}Ca, 3n) $^{294}_{118}$Og (Oganesson)

The names were accepted by IUPAC only in 2019 after independent confirmation of synthesis of these elements. Oganesson is the second element in the Periodic Table which has been named after a living scientist—Oganessian. There are some controversies between different research groups and IUPAC regarding the accepted dates and the pathways for first seen SHE.

The SHE story would be incomplete without mentioning the TASCA group at GSI, Darmstadt, Germany. In the early years of this century, GSI Kernchemie group along with many other experts designed and built a new device, TASCA (TransActinide Separator and Chemistry Apparatus). The main aim of TASCA was chemical studies of SHE. The emphasis was set on SHE produced in hot-fusion reactions. The Saha Institute of Nuclear Physics joined the TASCA group in 2003; first time Indian participation in SHE experiments. TASCA commissioning was completed in 2008. By the time, SHE research became extremely complicated, and multiple high-end instruments were required for successful SHE experiments. TASCA was coupled with highly efficient Focal Plane Detector, Recoil Transfer Chambers (RTC), Rotating wheel On-line Multidetector Analyser (ROMA) to further increase its efficiency. TASCA as a whole became the most versatile and highest efficient instrument in SHE researches worldwide. Since then numerous experiments have been carried out using TASCA facility by the international collaboration known as "TASCA Collaboration". For example, A gas chromatography experiment on Fl at TASCA was conducted earlier. (Yakushev *et al.* 2014). The experiment indicated the metallic character of Fl. Another noteworthy experiment was, production and decay of element 114 (Düllmann *et al.* 2010).

Table 2. Half-life and production rates of some superheavy elements.

Reaction	Half-life of the product	Production rate
^{248}Cm(^{18}O,5n)^{261}Rf	65 s	3 min^{-1}
^{249}Bk(^{18}O,5n)^{262}Db	34 s	2 min^{-1}
^{249}Cf(^{18}O,4n)^{263}Sg	0.8 s	6 h^{-1}
^{249}Bk(^{22}Ne,4n)^{267}Bh	–	1.5 h^{-1}
^{248}Cm(^{26}Mg,5n)^{269}Hs	9s	3 d^{-1}
^{238}U(^{48}Ca,3n)^{283}Cn	–	1 d^{-1}

The most noteworthy experiment so far at TASCA is the independent confirmation of new element 117 synthesized through ^{48}Ca + ^{249}Bk reaction (Khuyagbaatar *et al.* 2014). In total, sixteen institutes all over the world joined TASCA E-117 international collaboration, including the Saha Institute of Nuclear Physics, India. Element 117 was separated from many other nuclear reaction products in the TASCA and were identified through their radioactive decay. The collaboration identified two decay chains comprising seven α decays and a spontaneous fission (Figure 15). Both the α decays came from the isotope ^{294}117 and its decay products. A new isotope of Dubnium, ^{270}Db was discovered in the chain, whose half-life was determined as more than 1 h. The long half-life indicates the possibility of discovering the 'island of stability' in future.

Is it possible to synthesize elements beyond 118? TASCA collaboration performed long hunts in 2011 and 2012 for discovering elements 120 and 119 using ^{50}Ti+^{249}Cf and ^{50}Ti+^{249}Bk reactions respectively. However, no signature of E119 and E120 was observed.

Now a days, SHE experiment is a challenge. High energy, high current accelerators, excellent target preparation facilities, excellent separators (vacuum or

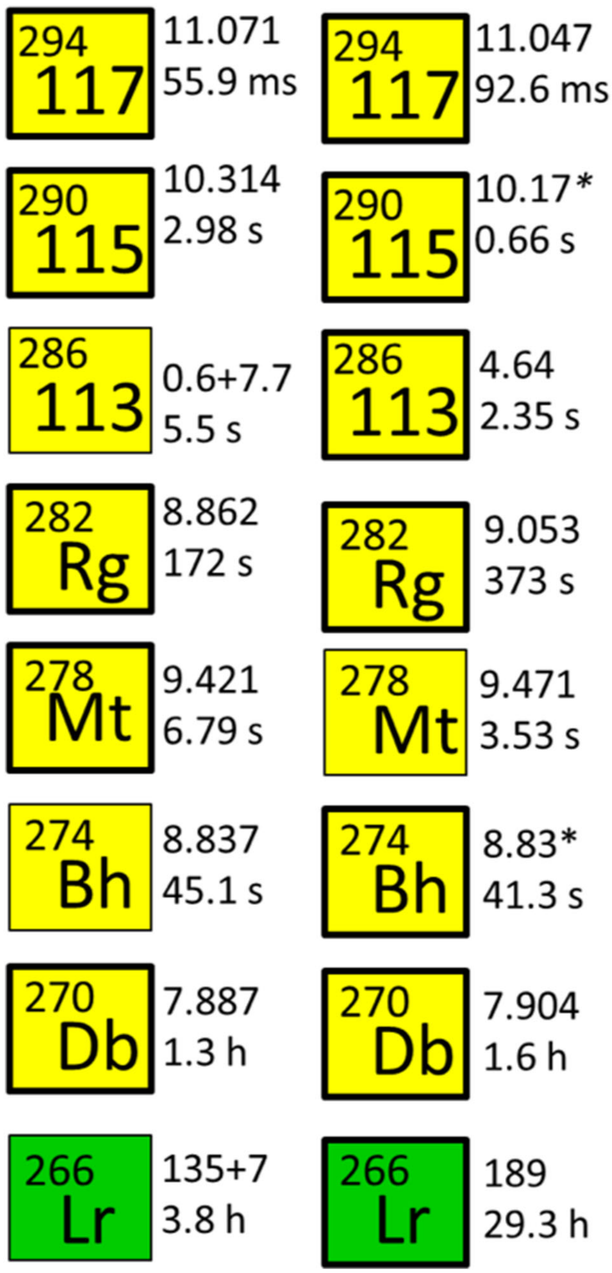

Figure 15. The two decay chains observed at TASCA during E-117 experiment (For details see Khuyagbaatar *et al.* 2014).

gas-filled), excellent detection systems like double-sided Si strip detector, advanced data analysis and acquisition systems are required for successful SHE experiments. Only a few centres worldwide, like GSI (Germany), FLNR, Dubna (Russia), LBNL (USA), RIKEN (Japan) are equipped with all these facilities. The Institute of Modern Physics, China is also joining the club. Many unknown properties of SHE are to be explored in near future. Limits of existence of chemical elements, volatility and reactivity of Cn and Fl, organometallic compounds of Rf to Hs, redox reactions of Sg to Hs, atomic and ionic radii of SHE are few identified and challenging problems. It is a long search and an exciting one.

9. Conclusion

The Periodic Table is a dynamic understanding of the properties of the elements. Therefore, the current shape of the Periodic Table is not the ultimate one. For example, Sato *et al.* (2015) determined the first ionization potential of lawrencium. The IP of Lr was measured with ^{256}Lr of half-life 27 seconds. They used an efficient surface ion-source coupled to a mass separator. They have shown that IP_1 of Lr is the lowest of all lanthanides and actinides, and the disorder of periodicity started at Lr. Their work triggered a discussion in IUPAC whether Lr is the last actinide, or it is better to shift Lu and Lr in group 3 below Sc and Y?

Acknowledgements

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