HOW FUNDAMENTAL SCIENCE HAS CHANGED THE WORLD

A STORY OF INVENTION AND DISCOVERY

Philipp Windischhofer

November 11, 2023
Reaping the fruits of hard work
Reaping the fruits of hard work
Reaping the fruits of hard work
Reaping the fruits of hard work
A new perspective on electricity

“Cathode Rays”
A new perspective on electricity
A new perspective on electricity

“Cathode rays” behave just like electricity!
A new perspective on electricity

“Cathode rays” behave just like electricity!
A new perspective on electricity

“Cathode rays” behave just like electricity!

Magnetic deflection

Electric deflection

Cathode rays
Cathode rays
Cathode rays

Electricity flowing in a wire
Mass $m$

Electric charge $e$

Cathode rays

Electricity flowing in a wire

J. J. Thomson (1897):

*Electricity is a stream of electrons*
What is the nature of electricity?
What is the nature of electricity?
Is matter continuous or discrete?
Is matter continuous or discrete?

A topic of “eternal” philosophical debate!
Is matter continuous or discrete?

A topic of “eternal” philosophical debate!

Democritus (ca. 300 BC):
Is matter continuous or discrete?

A topic of “eternal” philosophical debate!

Democritus (ca. 300 BC):

“By convention there is sweetness, by convention there is bitterness, by convention there is color; in reality only atoms and the void.”
Is matter continuous or discrete?

A topic of “eternal” philosophical debate!

Democritus (ca. 300 BC):

“By convention there is sweetness, by convention there is bitterness, by convention there is color; in reality only atoms and the void.”

“Bitterness is caused by small, angular, jagged atoms passing across the tongue.”
Is matter continuous or discrete?

A topic of “eternal” philosophical debate!

Democritus (ca. 300 BC):

“By convention there is sweetness, by convention there is bitterness, by convention there is color; in reality only atoms and the void.”

“Bitterness is caused by small, angular, jagged atoms passing across the tongue.”

“Sweetness is caused by larger, smoother, more rounded atoms.”
The first *real* hints: Chemistry

**Splitting substances with electricity**

*Early 1800s*

Water $\rightarrow$ Hydrogen + Oxygen
The first *real* hints: Chemistry

Splitting substances with electricity

*Early 1800s*

Water $\rightarrow$ Hydrogen + Oxygen
The first *real* hints: Chemistry

Splitting substances with electricity

*Early 1800s*

Water $\rightarrow$ Hydrogen + Oxygen

Volta’s battery
The first *real* hints: Chemistry

**Splitting substances with electricity**

*Early 1800s*

Water $\rightarrow$ Hydrogen + Oxygen

[Diagram showing a diagram of Volta's battery splitting water into hydrogen and oxygen]
The first *real* hints: Chemistry

**Splitting substances with electricity**

*Early 1800s*

Water → Hydrogen + Oxygen

[Diagram showing Volta's battery splitting water into hydrogen and oxygen]
The first *real* hints: Chemistry

Recombining substances

“When two measures of hydrogen and one of oxygen gas are mixed, and fired by the electric spark, the whole is converted into steam.”

\[
\text{Hydrogen} + \text{Oxygen} \rightarrow \text{Water}
\]

John Dalton
The first *real* hints: Chemistry

Recombining substances

“When two measures of hydrogen and one of oxygen gas are mixed, and fired by the electric spark, the whole is converted into steam.”

**Hydrogen** + **Oxygen** $\rightarrow$ **Water**

John Dalton
The first *real* hints: Chemistry

Recombining substances

“When two measures of hydrogen and one of oxygen gas are mixed, and fired by the electric spark, the whole is converted into steam.”

\[ \text{Hydrogen} + \text{Oxygen} \rightarrow \text{Water} \]

John Dalton

Carbon

100g
The first real hints: Chemistry

Recombining substances

“When two measures of hydrogen and one of oxygen gas are mixed, and fired by the electric spark, the whole is converted into steam.”

\[
\text{Hydrogen} + \text{Oxygen} \rightarrow \text{Water}
\]

\[
\begin{align*}
\text{Oxygen} & \quad 133g \\
\text{Carbon} & \quad 100g
\end{align*}
\]
The first real hints: Chemistry

Recombining substances

“When two measures of hydrogen and one of oxygen gas are mixed, and fired by the electric spark, the whole is converted into steam.”

\[
\text{Hydrogen + Oxygen} \rightarrow \text{Water}
\]

\[
\text{Carbon (100g)} \quad + \quad \text{Oxygen (133g)} \rightarrow \text{Carbon monoxide}
\]
The first real hints: Chemistry

Recombining substances

“When two measures of hydrogen and one of oxygen gas are mixed, and fired by the electric spark, the whole is converted into steam.”

\[
\text{Hydrogen} + \text{Oxygen} \rightarrow \text{Water}
\]

John Dalton

\[
\begin{align*}
\text{Carbon} & \quad 100g \\
+ & \\
\text{Oxygen} & \quad 133g \\
\rightarrow & \\
\text{Carbon monoxide} \\
+ & \\
\text{Oxygen} & \quad 266g
\end{align*}
\]
The first *real* hints: Chemistry

Recombining substances

“When two measures of hydrogen and one of oxygen gas are mixed, and fired by the electric spark, the whole is converted into steam.”

Hydrogen + Oxygen $\rightarrow$ Water

Carbon $100g$ + Oxygen $133g$ $\rightarrow$ Carbon monoxide

Carbon $100g$ + Oxygen $266g$ $\rightarrow$ Carbon dioxide

John Dalton
The first *real* hints: Chemistry

Recombining substances

“When two measures of hydrogen and one of oxygen gas are mixed, and fired by the electric spark, the whole is converted into steam.”

\[
\text{Hydrogen} + \text{Oxygen} \rightarrow \text{Water}
\]

Carbon 100g + Oxygen 133g → Carbon monoxide

Carbon 100g + Oxygen 266g → Carbon dioxide

John Dalton
The first real hints: Chemistry

Recombining substances

“When two measures of hydrogen and one of oxygen gas are mixed, and fired by the electric spark, the whole is converted into steam.”

\[
\text{Hydrogen} + \text{Oxygen} \rightarrow \text{Water}
\]

\[
\begin{align*}
\text{Carbon} & + \text{Oxygen} \\
& \quad \text{133g} \\
\quad \text{2:1} & \rightarrow \text{Carbon monoxide} \\
\end{align*}
\]

\[
\begin{align*}
\text{Carbon} & + \text{Oxygen} \\
& \quad \text{100g} \\
& \quad \text{266g} & \rightarrow \text{Carbon dioxide}
\end{align*}
\]

John Dalton
The first *real* hints: Chemistry

Recombining substances

“When two measures of hydrogen and one of oxygen gas are mixed, and fired by the electric spark, the whole is converted into steam.”

Hydrogen + Oxygen $\rightarrow$ Water

"Law of multiple proportions" (1804)
The first *real* hints: Chemistry

**Recombining substances**

“When two measures of hydrogen and one of oxygen gas are mixed, and fired by the electric spark, the whole is converted into steam.”

\[
\text{Hydrogen} + \text{Oxygen} \rightarrow \text{Water}
\]

John Dalton

“**Law of multiple proportions**” (1804)

Such ratios will always involve whole numbers!
Dalton’s atoms (1808)

“In all chemical investigations, all the changes we can produce consist in separating particles that are in a state of cohesion, and joining those that were previously at a distance.”
Dalton’s atoms (1808)

“In all chemical investigations, all the changes we can produce consist in separating particles that are in a state of cohesion, and joining those that were previously at a distance.”

1 atom of A + 1 atom of B = 1 atom of C
1 atom of A + 2 atoms of B = 1 atom of D
Dalton’s atoms (1808)

“In all chemical investigations, all the changes we can produce consist in separating particles that are in a state of cohesion, and joining those that were previously at a distance.”

\[
\begin{align*}
1 \text{ atom of } A &+ 1 \text{ atom of } B = 1 \text{ atom of } C \\
1 \text{ atom of } A &+ 2 \text{ atoms of } B = 1 \text{ atom of } D
\end{align*}
\]

“Water is a binary compound of hydrogen and oxygen, and the relative weights of the two elementary atoms are as 1 : 7.”
Dalton’s atoms (1808)

“In all chemical investigations, all the changes we can produce consist in separating particles that are in a state of cohesion, and joining those that were previously at a distance.”

\[
\begin{align*}
1 \text{ atom of } A & \rightarrow 1 \text{ atom of } B \rightarrow 1 \text{ atom of } C \\
1 \text{ atom of } A & \rightarrow 2 \text{ atoms of } B \rightarrow 1 \text{ atom of } D
\end{align*}
\]

“Water is a binary compound of hydrogen and oxygen, and the relative weights of the two elementary atoms are as 1 : 7.”

1) Atoms are elementary
Dalton’s atoms (1808)

“In all chemical investigations, all the changes we can produce consist in separating particles that are in a state of cohesion, and joining those that were previously at a distance.”

```
1 atom of A + 1 atom of B = 1 atom of C
1 atom of A + 2 atoms of B = 1 atom of D
```

“Water is a binary compound of hydrogen and oxygen, and the relative weights of the two elementary atoms are as 1 : 7.”

1) Atoms are elementary

2) As such, they only come in whole numbers
Dalton’s atoms (1808)

“In all chemical investigations, all the changes we can produce consist in separating particles that are in a state of cohesion, and joining those that were previously at a distance.”

“Water is a binary compound of hydrogen and oxygen, and the relative weights of the two elementary atoms are as 1 : 7.”

1) Atoms are elementary

2) As such, they only come in whole numbers

3) The masses of different atoms relate to each other as whole numbers
Dalton’s atoms (1808)

“In all chemical investigations, all the changes we can produce consist in separating particles that are in a state of cohesion, and joining those that were previously at a distance.”

1 atom of A + 1 atom of B = 1 atom of C
1 atom of A + 2 atoms of B = 1 atom of D

“Water is a binary compound of hydrogen and oxygen, and the relative weights of the two elementary atoms are as 1 : 7.”

Wrong! It’s 1:16!

1) Atoms are elementary

2) As such, they only come in whole numbers

3) The masses of different atoms relate to each other as whole numbers
Dalton’s atoms (1808)
Dalton’s atoms (1808)

Table of relative atomic weights:

<table>
<thead>
<tr>
<th>Fig.</th>
<th>Element</th>
<th>Relative Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrog. its rel.  weight</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Azote</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Carbone or charcoal</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Oxygen</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>Phosphorus</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>Sulphur</td>
<td>13</td>
</tr>
<tr>
<td>7</td>
<td>Magnesia</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>Lime</td>
<td>23</td>
</tr>
<tr>
<td>9</td>
<td>Soda</td>
<td>28</td>
</tr>
<tr>
<td>10</td>
<td>Potash</td>
<td>42</td>
</tr>
<tr>
<td>11</td>
<td>Strontites</td>
<td>46</td>
</tr>
<tr>
<td>12</td>
<td>Barytes</td>
<td>68</td>
</tr>
<tr>
<td>13</td>
<td>Iron</td>
<td>38</td>
</tr>
<tr>
<td>14</td>
<td>Zinc</td>
<td>56</td>
</tr>
<tr>
<td>15</td>
<td>Copper</td>
<td>56</td>
</tr>
<tr>
<td>16</td>
<td>Lead</td>
<td>95</td>
</tr>
<tr>
<td>17</td>
<td>Silver</td>
<td>100</td>
</tr>
<tr>
<td>18</td>
<td>Platina</td>
<td>100</td>
</tr>
<tr>
<td>19</td>
<td>Gold</td>
<td>140</td>
</tr>
<tr>
<td>20</td>
<td>Mercury</td>
<td>167</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td></td>
<td></td>
</tr>
<tr>
<td>36</td>
<td></td>
<td></td>
</tr>
<tr>
<td>37</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Dalton’s atoms (1808)

Table of relative atomic weights:

<table>
<thead>
<tr>
<th>Fig.</th>
<th>Element</th>
<th>Relative Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrogen</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Azote</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Carbon or charcoal</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Oxygen</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>Phosphorus</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>Sulphur</td>
<td>13</td>
</tr>
<tr>
<td>7</td>
<td>Magnesia</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>Lime</td>
<td>23</td>
</tr>
<tr>
<td>9</td>
<td>Soda</td>
<td>28</td>
</tr>
<tr>
<td>10</td>
<td>Potash</td>
<td>42</td>
</tr>
<tr>
<td>11</td>
<td>Strontium</td>
<td>46</td>
</tr>
<tr>
<td>12</td>
<td>Barytes</td>
<td>68</td>
</tr>
<tr>
<td>13</td>
<td>Iron</td>
<td>38</td>
</tr>
<tr>
<td>14</td>
<td>Zinc</td>
<td>56</td>
</tr>
<tr>
<td>15</td>
<td>Copper</td>
<td>56</td>
</tr>
<tr>
<td>16</td>
<td>Lead</td>
<td>95</td>
</tr>
<tr>
<td>17</td>
<td>Silver</td>
<td>100</td>
</tr>
<tr>
<td>18</td>
<td>Platina</td>
<td>100</td>
</tr>
<tr>
<td>19</td>
<td>Gold</td>
<td>140</td>
</tr>
<tr>
<td>20</td>
<td>Mercury</td>
<td>167</td>
</tr>
</tbody>
</table>

On the nature of atoms:
Dalton’s atoms (1808)

Table of relative atomic weights:

<table>
<thead>
<tr>
<th>Fig.</th>
<th>Atom</th>
<th>Relative Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hydrogen</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Azote</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Carbone or charcoal</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Oxygen</td>
<td>7</td>
</tr>
<tr>
<td>5</td>
<td>Phosphorus</td>
<td>9</td>
</tr>
<tr>
<td>6</td>
<td>Sulphur</td>
<td>13</td>
</tr>
<tr>
<td>7</td>
<td>Magnesia</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>Lime</td>
<td>25</td>
</tr>
<tr>
<td>9</td>
<td>Soda</td>
<td>28</td>
</tr>
<tr>
<td>10</td>
<td>Potash</td>
<td>42</td>
</tr>
<tr>
<td>11</td>
<td>Strontites</td>
<td>46</td>
</tr>
<tr>
<td>12</td>
<td>Barytes</td>
<td>68</td>
</tr>
<tr>
<td>13</td>
<td>Iron</td>
<td>38</td>
</tr>
<tr>
<td>14</td>
<td>Zinc</td>
<td>56</td>
</tr>
<tr>
<td>15</td>
<td>Copper</td>
<td>56</td>
</tr>
<tr>
<td>16</td>
<td>Lead</td>
<td>95</td>
</tr>
<tr>
<td>17</td>
<td>Silver</td>
<td>100</td>
</tr>
<tr>
<td>18</td>
<td>Platina</td>
<td>100</td>
</tr>
<tr>
<td>19</td>
<td>Gold</td>
<td>140</td>
</tr>
<tr>
<td>20</td>
<td>Mercury</td>
<td>167</td>
</tr>
</tbody>
</table>

On the nature of atoms:

“The atoms of such bodies are conceived at present to be simple.”
**Dalton’s atoms (1808)**

Table of relative atomic weights:

<table>
<thead>
<tr>
<th>Fig.</th>
<th>1 Hydrog. its rel. weight</th>
<th>2 Azote</th>
<th>3 Carbone or charcoal</th>
<th>4 Oxygen</th>
<th>5 Phosphorus</th>
<th>6 Sulphur</th>
<th>7 Magnesia</th>
<th>8 Lime</th>
<th>9 Soda</th>
<th>10 Potash</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td>9</td>
<td>13</td>
<td>20</td>
<td>23</td>
<td>28</td>
<td>42</td>
</tr>
<tr>
<td>Fig.</td>
<td>11 Strontites</td>
<td>12 Barytes</td>
<td>13 Iron</td>
<td>14 Zinc</td>
<td>15 Copper</td>
<td>16 Lead</td>
<td>17 Silver</td>
<td>18 Platina</td>
<td>19 Gold</td>
<td>20 Mercury</td>
</tr>
<tr>
<td></td>
<td>46</td>
<td>68</td>
<td>38</td>
<td>56</td>
<td>56</td>
<td>95</td>
<td>100</td>
<td>100</td>
<td>140</td>
<td>167</td>
</tr>
</tbody>
</table>

Some are close, but most are wrong!

**On the nature of atoms:**

“The atoms of such bodies are conceived at present to be simple.”
Yet more regularity

1863: 56 chemical elements (ca. 1 new discovery per year)

Is there any order in this chaos?
Yet more regularity

1863: 56 chemical elements (ca. 1 new discovery per year)

Is there any order in this chaos?

Dmitri Mendeleev

Mendeleev's table (1871)
Yet more regularity

1863: 56 chemical elements *(ca. 1 new discovery per year)*

*Is there any order in this chaos?*

---

<table>
<thead>
<tr>
<th>Periods</th>
<th>Elements</th>
<th>Chemically Similar Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>Li, Be, B, C, N, O</td>
<td>8 groups of similar elements</td>
</tr>
<tr>
<td>3-4</td>
<td>Na, Mg, Al, Si, P, S, Cl, Ar</td>
<td>8 groups of similar elements</td>
</tr>
<tr>
<td>5-6</td>
<td>K, Ca, Sc, Ti, V, Cr, Mn, Fe</td>
<td>8 groups of similar elements</td>
</tr>
<tr>
<td>7-8</td>
<td>Rb, Sr, Y, Zr, Nb, Mo, Ru, Rh</td>
<td>8 groups of similar elements</td>
</tr>
<tr>
<td>9</td>
<td>Cs, Ba, La, Hf, Ta, W, Os, Ir</td>
<td>8 groups of similar elements</td>
</tr>
<tr>
<td>10</td>
<td>Fr, Ra, Ac, Th, U</td>
<td>8 groups of similar elements</td>
</tr>
</tbody>
</table>

---

Mendeleev's table *(1871)*

---

Dmitri Mendeleev
Yet more regularity

1863: 56 chemical elements *(ca. 1 new discovery per year)*

*Is there any order in this chaos?*

**Apparent periodicity! Missing elements!**

Eight groups of chemically similar elements

---

**Dmitri Mendeleev**

---

**Mendeleev’s table (1871)**
Yet more regularity

1863: 56 chemical elements (ca. 1 new discovery per year)

Is there any order in this chaos?

Apparent periodicity! Missing elements!

Eight groups of chemically similar elements

Dmitri Mendeleev

Mendeleev’s table (1871)
Yet more regularity

1863: 56 chemical elements *(ca. 1 new discovery per year)*

*Is there any order in this chaos?*

Apparent periodicity! Missing elements!

Eight groups of chemically similar elements

Dmitri Mendeleev

Mendeleev’s table *(1871)*

<table>
<thead>
<tr>
<th>Period</th>
<th>Group I. (R)</th>
<th>Group II. (R)</th>
<th>Group III. (R)</th>
<th>Group IV. (R)</th>
<th>Group V. (R)</th>
<th>Group VI. (R)</th>
<th>Group VII. (R)</th>
<th>Group VIII. (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H = 1</td>
<td>Li = 7</td>
<td>Be = 2.4</td>
<td>B = 11</td>
<td>C = 12</td>
<td>N = 14</td>
<td>O = 16</td>
<td>F = 19</td>
</tr>
<tr>
<td>2</td>
<td>Na = 11</td>
<td>Mg = 16</td>
<td>Al = 13.5</td>
<td>Si = 14</td>
<td>P = 15</td>
<td>S = 16</td>
<td>Cl = 17.5</td>
<td>Ar = 18</td>
</tr>
<tr>
<td>3</td>
<td>K = 19</td>
<td>Ca = 20.1</td>
<td>Sc = 47</td>
<td>Ti = 47</td>
<td>V = 50</td>
<td>Cr = 52</td>
<td>Mn = 55</td>
<td>Fe = 56</td>
</tr>
<tr>
<td>4</td>
<td>(Ca = 63)</td>
<td>Sr = 87</td>
<td>Y = 88</td>
<td>Zr = 91</td>
<td>Nb = 93</td>
<td>Mo = 95</td>
<td>Tc = 100</td>
<td>Ru = 104</td>
</tr>
<tr>
<td>5</td>
<td>Rb = 37</td>
<td>Cs = 133</td>
<td>Ba = 137</td>
<td>Ra = 226</td>
<td>Th = 234</td>
<td>Pa = 242</td>
<td>U = 248</td>
<td>Np = 259</td>
</tr>
<tr>
<td>6</td>
<td>(Ag = 105)</td>
<td>Cd = 112</td>
<td>In = 113</td>
<td>Sn = 119</td>
<td>Sb = 122</td>
<td>Te = 125</td>
<td>I = 127</td>
<td>Xe = 131</td>
</tr>
<tr>
<td>7</td>
<td>(Au = 197)</td>
<td>Hg = 200</td>
<td>Tl = 204</td>
<td>Pb = 207</td>
<td>Bi = 209</td>
<td>Po = 210</td>
<td>At = 210</td>
<td>Rn = 222</td>
</tr>
<tr>
<td>8</td>
<td>(Pb = 207)</td>
<td>Th = 234</td>
<td>Pa = 242</td>
<td>U = 248</td>
<td>Np = 259</td>
<td>Pu = 248</td>
<td>Am = 243</td>
<td>Cm = 247</td>
</tr>
<tr>
<td>9</td>
<td>(U = 248)</td>
<td>(&amp;)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Yet more regularity

1863: 56 chemical elements (ca. 1 new discovery per year)

*Is there any order in this chaos?*

Apparent periodicity! Missing elements!

Eight groups of chemically similar elements

---

<table>
<thead>
<tr>
<th>Period</th>
<th>Group I</th>
<th>Group II</th>
<th>Group III</th>
<th>Group IV</th>
<th>Group V</th>
<th>Group VI</th>
<th>Group VII</th>
<th>Group VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R¹O</td>
<td>R²O</td>
<td>R³O</td>
<td>R⁴O</td>
<td>R⁵O</td>
<td>R⁶O</td>
<td>R⁷O</td>
<td>R⁸O</td>
</tr>
<tr>
<td>1</td>
<td>H=1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>Li=7</td>
<td>—</td>
<td>B=2.4</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>5</td>
<td>Na=23</td>
<td>Mg=24</td>
<td>Al=27.8</td>
<td>Si=28</td>
<td>P=31</td>
<td>S=32</td>
<td>Cl=35.5</td>
<td>—</td>
</tr>
<tr>
<td>4</td>
<td>K=39</td>
<td>Ca=40</td>
<td>Ti=48</td>
<td>V=51</td>
<td>Cr=52</td>
<td>Mn=56</td>
<td>Fe=56, Co=60, Ni=69, Cu=63.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>(Cu=63)</td>
<td>Zn=65</td>
<td>—</td>
<td>As=75</td>
<td>Se=73</td>
<td>Br=80</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>6</td>
<td>Rb=86</td>
<td>Sr=87</td>
<td>Y=88</td>
<td>Zr=90</td>
<td>Nb=94</td>
<td>Mo=98</td>
<td>Ru=104, Rh=104, Pd=106, Ag=168.</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>(Ag=105)</td>
<td>Cd=112</td>
<td>In=113</td>
<td>Sn=118</td>
<td>Sb=122</td>
<td>Te=125</td>
<td>I=127</td>
<td>—</td>
</tr>
<tr>
<td>8</td>
<td>Cs=183</td>
<td>Ba=137</td>
<td>Th=231</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>9</td>
<td>(--)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>10</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>11</td>
<td>(An=199)</td>
<td>Hg=200</td>
<td>Tl=204</td>
<td>Pb=207</td>
<td>Bi=209</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>12</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>Th=231</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Dmitri Mendeleev

Mendeleev's table (1871)
Yet more regularity

1863: 56 chemical elements *(ca. 1 new discovery per year)*

*Is there any order in this chaos?*

Apparent periodicity! Missing elements!

Eight groups of chemically similar elements

---

**Mendeleev’s table (1871)**
Yet more regularity

1863: 56 chemical elements (ca. 1 new discovery per year)

Is there any order in this chaos?

Apparent periodicity! Missing elements!

Eight groups of chemically similar elements

Dmitri Mendeleev

Mendeleev’s table (1871)
Yet more regularity

1863: 56 chemical elements *(ca. 1 new discovery per year)*

*Is there any order in this chaos?*

Apparent periodicity! Missing elements!

<table>
<thead>
<tr>
<th>Period</th>
<th>Group I</th>
<th>Group II</th>
<th>Group III</th>
<th>Group IV, RH</th>
<th>Group V, RH</th>
<th>Group VI, RH</th>
<th>Group VII, RH</th>
<th>Group VIII, RH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R'0</td>
<td>R0</td>
<td>R'0</td>
<td>R0</td>
<td>R'0</td>
<td>R0</td>
<td>R'0</td>
<td>R0</td>
</tr>
<tr>
<td>1</td>
<td>H=1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Li=7</td>
<td>Be=4,4</td>
<td>B=11</td>
<td>C=12</td>
<td>N=14</td>
<td>O=16</td>
<td>F=19</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Na=23</td>
<td>Mg=24</td>
<td>Al=27,8</td>
<td>Si=26</td>
<td>P=31</td>
<td>S=32</td>
<td>Cl=35,5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>K=39</td>
<td>Ca=40</td>
<td>Ti=48</td>
<td>V=51</td>
<td>Cr=52</td>
<td>Mn=55</td>
<td>Fe=56, Co=60, Ni=69, Cu=63.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>(Ca=63)</td>
<td>Zn=65</td>
<td>=66</td>
<td>As=75</td>
<td>Se=73</td>
<td>Br=80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Rb=86</td>
<td>Sr=87</td>
<td>Y=88</td>
<td>Zr=90</td>
<td>Nb=94</td>
<td>Mo=90</td>
<td>Ru=104, Rh=104, Pd=106, Ag=108.</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>(Ag=105)</td>
<td>Cd=112</td>
<td>In=113</td>
<td>Sn=118</td>
<td>Sb=122</td>
<td>Te=125</td>
<td>J=127</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Cs=133</td>
<td>Ba=137</td>
<td>(Di=138)</td>
<td>Ce=140</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>(--)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>Te=178</td>
<td>La=180</td>
<td>Ta=182</td>
<td>W=184</td>
<td>Os=196, Ir=197, Pt=198, Au=199.</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>(Au=199)</td>
<td>Hg=200</td>
<td>Tl=204</td>
<td>Pb=207</td>
<td>Bi=209</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
<td>Th=231</td>
<td>U=240</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Dmitri Mendeleev

Mendeleev's table *(1871)*
Yet more regularity

1863: 56 chemical elements *(ca. 1 new discovery per year)*

*Is there any order in this chaos?*

Apparent periodicity! Missing elements!

Eight groups of chemically similar elements

---

Dmitri Mendeleev

---

Mendeleev's table *(1871)*
Yet more regularity

1863: 56 chemical elements *(ca. 1 new discovery per year)*

*Is there any order in this chaos?*

Apparent periodicity! Missing elements!

Eight groups of chemically similar elements

<table>
<thead>
<tr>
<th>Rech.</th>
<th>Gruppo I.</th>
<th>Gruppo II.</th>
<th>Gruppo III.</th>
<th>Gruppo IV.</th>
<th>Gruppo V.</th>
<th>Gruppo VI.</th>
<th>Gruppo VII.</th>
<th>Gruppo VIII.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>— R0°</td>
<td>— R0°</td>
<td>— R0°</td>
<td>— R0°</td>
<td>— R0°</td>
<td>— R0°</td>
<td>— R0°</td>
<td>— R0°</td>
</tr>
<tr>
<td>1</td>
<td>H=1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>Li=7</td>
<td>Be=4,4</td>
<td>Be=4</td>
<td>Be=4,4</td>
<td>Be=4</td>
<td>Be=4,4</td>
<td>Be=4</td>
<td>Be=4,4</td>
</tr>
<tr>
<td>3</td>
<td>—</td>
<td>[Mg=24]</td>
<td>[Mg=24]</td>
<td>[Mg=24]</td>
<td>[Mg=24]</td>
<td>[Mg=24]</td>
<td>[Mg=24]</td>
<td>[Mg=24]</td>
</tr>
<tr>
<td>4</td>
<td>K=39</td>
<td>Ca=40</td>
<td>Ca=40</td>
<td>Ca=40</td>
<td>Ca=40</td>
<td>Ca=40</td>
<td>Ca=40</td>
<td>Ca=40</td>
</tr>
<tr>
<td>5</td>
<td>Na=23</td>
<td>Mg=24</td>
<td>Al=27,8</td>
<td>Si=26</td>
<td>P=31</td>
<td>S=32</td>
<td>Cl=35,5</td>
<td>Mn=65</td>
</tr>
<tr>
<td>6</td>
<td>—</td>
<td>Zn=65</td>
<td>—=66</td>
<td>—=72</td>
<td>—=72</td>
<td>—=72</td>
<td>—=72</td>
<td>—=72</td>
</tr>
<tr>
<td>7</td>
<td>K=39</td>
<td>Ca=40</td>
<td>Al=27,8</td>
<td>Si=26</td>
<td>P=31</td>
<td>S=32</td>
<td>Cl=35,5</td>
<td>Mn=65</td>
</tr>
<tr>
<td>8</td>
<td>Rb=86</td>
<td>Sr=87</td>
<td>—=66</td>
<td>—=72</td>
<td>—=72</td>
<td>—=72</td>
<td>—=72</td>
<td>—=72</td>
</tr>
<tr>
<td>9</td>
<td>Cs=133</td>
<td>Ba=137</td>
<td>—=66</td>
<td>—=72</td>
<td>—=72</td>
<td>—=72</td>
<td>—=72</td>
<td>—=72</td>
</tr>
<tr>
<td>10</td>
<td>(–)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>11</td>
<td>Hg=200</td>
<td>Tl=204</td>
<td>Pb=207</td>
<td>Bi=209</td>
<td>U=240</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>12</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Dmitri Mendeleev

Mendeleev’s table *(1871)*
Yet more regularity

1863: 56 chemical elements (ca. 1 new discovery per year)

Is there any order in this chaos?

Apparent periodicity! Missing elements!

Eight groups of chemically similar elements

Mendeleev’s table (1871)
Yet more regularity

1863: 56 chemical elements (*ca. 1 new discovery per year*)

*Is there any order in this chaos?*

Apparent periodicity! Missing elements!

<table>
<thead>
<tr>
<th>Period</th>
<th>Gruppo I</th>
<th>Gruppo II</th>
<th>Gruppo III</th>
<th>Gruppo IV, RH</th>
<th>Gruppo V, RH</th>
<th>Gruppo VI</th>
<th>Gruppo VII</th>
<th>Gruppo VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R₀</td>
<td>R₀'</td>
<td>R₀''</td>
<td>R₀³</td>
<td>R₀⁴</td>
<td>R₀⁵</td>
<td>R₀⁶</td>
<td>R₀⁷</td>
</tr>
<tr>
<td>1</td>
<td>H (1)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>Li (7)</td>
<td>Be (4)</td>
<td>B (3)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>3</td>
<td>Na (11)</td>
<td>Mg (12)</td>
<td>Al (13)</td>
<td>Si (14)</td>
<td>P (15)</td>
<td>S (16)</td>
<td>Cl (17)</td>
<td>Ar (18)</td>
</tr>
<tr>
<td>4</td>
<td>K (19)</td>
<td>Ca (20)</td>
<td>Sc (21)</td>
<td>Ti (22)</td>
<td>V (23)</td>
<td>Cr (24)</td>
<td>Mn (25)</td>
<td>Fe (26)</td>
</tr>
<tr>
<td>5</td>
<td>(Ca = 63)</td>
<td>Zn (65)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>6</td>
<td>Rb (37)</td>
<td>Sr (38)</td>
<td>Y (39)</td>
<td>Zr (40)</td>
<td>Nb (41)</td>
<td>Mo (42)</td>
<td>Tc (43)</td>
<td>Ru (44)</td>
</tr>
<tr>
<td>7</td>
<td>(Ag = 105)</td>
<td>Cd (112)</td>
<td>In (113)</td>
<td>Sn (114)</td>
<td>Pb (115)</td>
<td>Bi (116)</td>
<td>Po (117)</td>
<td>At (118)</td>
</tr>
<tr>
<td>8</td>
<td>Cs (133)</td>
<td>Ba (134)</td>
<td>La (135)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>9</td>
<td>(--)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>10</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>11</td>
<td>(Au = 197)</td>
<td>Hg (200)</td>
<td>Tl (204)</td>
<td>Pb (207)</td>
<td>Bi (208)</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>12</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Eight groups of chemically similar elements

Mendeleev’s table (1871)

Dmitri Mendeleev
“Thus on this view, we have in the cathode rays matter in a new state, a state in which the subdivision of matter is carried very much further than in the ordinary gaseous state.”
Thomson’s view of the atom (1904)

Normal matter is electrically neutral

→ Atoms are electrically neutral
Thomson’s view of the atom (1904)

Normal matter is electrically neutral

→ Atoms are electrically neutral

“We suppose that the atom consists of a number of corpuscles moving about in a sphere of uniform positive electrification.”
Thomson’s view of the atom (1904)

Normal matter is electrically neutral

→ Atoms are electrically neutral

“We suppose that the atom consists of a number of corpuscles moving about in a sphere of uniform positive electrification.”
Thomson’s view of the atom (1904)

Normal matter is electrically neutral

→ Atoms are electrically neutral

“We suppose that the atom consists of a number of corpuscles moving about in a sphere of uniform positive electrification.”
Thomson’s view of the atom (1904)

“What properties would this structure confer upon the atom?”
Thomson’s view of the atom (1904)

“What properties would this structure confer upon the atom?”

“Stability suggests the view of a motion of a ring of negatively electrified particles placed inside a uniformly electrified sphere.”
Thomson’s view of the atom (1904)

“What properties would this structure confer upon the atom?”

“Stability suggests the view of a motion of a ring of negatively electrified particles placed inside a uniformly electrified sphere.”
“What properties would this structure confer upon the atom?”

“Stability suggests the view of a motion of a ring of negatively electrified particles placed inside a uniformly electrified sphere.”
Thomson’s view of the atom (1904)

“What properties would this structure confer upon the atom?”

“Stability suggests the view of a motion of a ring of negatively electrified particles placed inside a uniformly electrified sphere.”
“What properties would this structure confer upon the atom?”

“Stability suggests the view of a motion of a ring of negatively electrified particles placed inside a uniformly electrified sphere.”

“A large number of particles cannot be in a stable equilibrium when arranged as a single ring.”
Thomson’s view of the atom (1904)

“What properties would this structure confer upon the atom?”

“Stability suggests the view of a motion of a ring of negatively electrified particles placed inside a uniformly electrified sphere.”

“A large number of particles cannot be in a stable equilibrium when arranged as a single ring.”

“It can be made stable by placing inside it an appropriate number of corpuscles.”
Thomson’s view of the atom (1904)

“It can be made stable by placing inside it an appropriate number of corpuscles.”
Thomson’s view of the atom (1904)

“It can be made stable by placing inside it an appropriate number of corpuscles.”

“Shells”
Thomson’s view of the atom (1904)

“It can be made stable by placing inside it an appropriate number of corpuscles.”

What would be the chemical properties of such atoms?
Thomson’s view of the atom (1904)

“It can be made stable by placing inside it an appropriate number of corpuscles.”

“Shells”

What would be the chemical properties of such atoms?

Can the laws of mechanics and electricity explain chemistry?
Thomson’s view of the atom (1904)

Adding more and more corpuscles: heavier atoms (in discrete jumps!)
Thomson’s view of the atom (1904)

Adding more and more corpuscles: heavier atoms *(in discrete jumps!)*

This sequence of properties is very like that observed in the case of the atoms of the elements.

Thus we have the series of elements:

\[
\text{He Li Be B C N O F Ne.} \\
\text{Ne Na Mg Al Si P S Cl Arg.}
\]

The first and last element in each of these series has no valency, the second is a monovalent electropositive element, the last but one is a monovalent electronegative element, the third is a divalent electropositive element, the last but two a divalent electronegative element, and so on.
Thomson’s view of the atom (1904)

Adding more and more corpuscles: heavier atoms (in discrete jumps!)

“Plum Pudding model”

Electrons are like raisins in a cake!

The first and last element in each of these series has no valency, the second is a monovalent electropositive element, the last but one is a monovalent electronegative element, the third is a divalent electropositive element, the last but two a divalent electronegative element, and so on.
How to look inside the atom?
How to look inside the atom?

Back ten years to Röntgen and his X-rays …
Röntgen’s big discovery (1895)

Crookes’ tube

Obstacle
(Wood, metal, …)

Fluorescent screen

X-rays

Used widely-available equipment
→ surge of interest from other scientists
Henri Becquerel
Henri Becquerel

His doctoral thesis:
“Researches on the absorption of light by crystals”
Henri Becquerel

His doctoral thesis:
“Researches on the absorption of light by crystals”
Henri Becquerel

His doctoral thesis:
“Researches on the absorption of light by crystals”
Henri Becquerel

His doctoral thesis:
“Researches on the absorption of light by crystals”

1895: Professor at Ecole Polytechnique
(Ca. 80 years after Sadi Carnot)
Phosphorescence and uranium

Uranium salt exposed to sunlight ...

“Phosphorescence”
Phosphorescence and uranium

Uranium salt exposed to sunlight ...

... continues to glow in the dark for a certain time

“Phosphorescence”
Phosphorescence and uranium

Uranium salt exposed to sunlight in the dark will continue to glow in the dark for a certain time. "Phosphorescence"

White phosphorus also glows in the dark!
At the Academy of Sciences in 1896
At the Academy of Sciences in 1896

“Mr. H. Poincaré had just shown the first radiographs sent by Mr. Röntgen.”
At the Academy of Sciences in 1896

“Mr. H. Poincaré had just shown the first radiographs sent by Mr. Röntgen.”
At the Academy of Sciences in 1896

“Mr. H. Poincaré had just shown the first radiographs sent by Mr. Röntgen.”

“I asked my colleague what was the place of emission of those rays, in the vacuum tube that produced X-rays.”
At the Academy of Sciences in 1896

“Mr. H. Poincaré had just shown the first radiographs sent by Mr. Röntgen.”

“I asked my colleague what was the place of emission of those rays, in the vacuum tube that produced X-rays.”
At the Academy of Sciences in 1896

“Mr. H. Poincaré had just shown the first radiographs sent by Mr. Röntgen.”

“I asked my colleague what was the place of emission of those rays, in the vacuum tube that produced X-rays.”

“I was answered that the origin of the radiation was the luminous spot of the wall of the tube that received the cathodic flux.”
At the Academy of Sciences in 1896

“Mr. H. Poincaré had just shown the first radiographs sent by Mr. Röntgen.”

“I asked my colleague what was the place of emission of those rays, in the vacuum tube that produced X-rays.”

“I was answered that the origin of the radiation was the luminous spot of the wall of the tube that received the cathodic flux.”
At the Academy of Sciences in 1896

“Mr. H. Poincaré had just shown the first radiographs sent by Mr. Röntgen.”

“I asked my colleague what was the place of emission of those rays, in the vacuum tube that produced X-rays.”

“I was answered that the origin of the radiation was the luminous spot of the wall of the tube that received the cathodic flux.”

“I cogitated at once to search whether the new emission was a manifestation of the phenomenon that gave birth to the phosphorescence and whether all phosphorescent bodies emit similar rays.”
A chance discovery

“A Lumière plate was enclosed in an opaque case of black cloth.”
A chance discovery

“A Lumière plate was enclosed in an opaque case of black cloth.”

Uranium salt

Wrapped photographic plate
A chance discovery

“A Lumièrè plate was enclosed in an opaque case of black cloth.”

“After developing the photographic plate in the usual way, one observes that the silhouette of the crystalline crust appears in black on the sensitive plate.”

Wrapped photographic plate

Uranium salt
A chance discovery

“A Lumière plate was enclosed in an opaque case of black cloth.”

“After developing the photographic plate in the usual way, one observes that the silhouette of the crystalline crust appears in black on the sensitive plate.”
A chance discovery

“A Lumière plate was enclosed in an opaque case of black cloth.”
A chance discovery

“A Lumière plate was enclosed in an opaque case of black cloth.”

“I will insist particularly upon the following fact, which seems to me quite important and beyond the phenomena which one could expect to observe.”
A chance discovery

“A Lumière plate was enclosed in an opaque case of black cloth.”

“\[\text{source} \]

Wrapped photographic plate

Uranium salt

“I will insist particularly upon the following fact, which seems to me quite important and beyond the phenomena which one could expect to observe.”

“The same crystalline crusts, arranged the same way, in the same conditions and through the same screens, but kept in darkness, still produce the same photographic images.”
A chance discovery

“A Lumière plate was enclosed in an opaque case of black cloth.”

“I will insist particularly upon the following fact, which seems to me quite important and beyond the phenomena which one could expect to observe.”

“The same crystalline crusts, arranged the same way, in the same conditions and through the same screens, but kept in darkness, still produce the same photographic images.”
A chance discovery

“A Lumière plate of black cloth.”

Wrapped photographic plate

Uranium salt

“I will insist particularly upon the following fact, which seems to me quite important and beyond the phenomena which one could expect to observe.”

“The same crystalline crusts, arranged the same way, in the same conditions and through the same screens, but kept in darkness, still produce the same photographic images.”

[source]
A chance discovery

“A Lumière plate of black cloth.”

Wrapped photographic plate → Uranium salt → Wrapped photographic plate

“I will insist particularly upon the following fact, which seems to me quite important and beyond the phenomena which one could expect to observe.”

“The same crystalline crusts, arranged the same way, in the same conditions and through the same screens, but kept in darkness, still produce the same photographic images.”

It’s not about the sun nor phosphorescence at all!
A chance discovery

“A Lumière plate of black cloth.”

Wrapped photographic plate

Uranium salt

These effects have a great similarity to the effects produced by the rays studied by Mr. Röntgen.”

It’s not about the sun nor phosphorescence at all!
Marie Skłodowska-Curie
Marie Skłodowska-Curie

From Poland to Paris: A pact between sisters
Marie Skłodowska-Curie

From Poland to Paris:
A pact between sisters

Arrived in Paris in 1891:
Just after the World’s Fair in 1889
From Poland to Paris: A pact between sisters

Arrived in Paris in 1891:
Just after the World’s Fair in 1889

The Latin Quarter
Marie Skłodowska-Curie

From Poland to Paris: A pact between sisters

Arrived in Paris in 1891: Just after the World’s Fair in 1889

The Latin Quarter

A Narrow Street in the Latin Quarter of Paris, France. Copyright 1900 by Underwood & Underwood.
1880: the Curie brothers discover the piezoelectric effect
1880: the Curie brothers discover the piezoelectric effect

1895: Magnets lose their magnetism when heated up!
The Curies in 1895
The Curies in 1895

Enjoying their honeymoon (1895)
The Curies in 1895

Enjoying their honeymoon (1895)

1896: Marie is looking for a doctoral thesis topic
How to quantify the strength of Becquerel’s radiation?
A connection with electricity
A connection with electricity

Leyden jar
("Cylindrical condenser")

Metal foil
A connection with electricity

Leyden jar
("Cylindrical condenser")

Metal foil

“Parallel-plate condenser”

“Becquerel rays” are “ionizing”
A connection with electricity

- Leyden jar ("Cylindrical condenser")
- Metal foil
- "Becquerel rays" are "ionizing"
- "Parallel-plate condenser"
A connection with electricity

Metal foil

Leyden jar
("Cylindrical condenser")

"Parallel-plate condenser"

"Becquerel rays" are "ionizing"
A connection with electricity

Metal foil

Leyden jar
("Cylindrical condenser")

“Becquerel rays”
are “ionizing”

“Parallel-plate condenser”
A connection with electricity

Leyden jar
("Cylindrical condenser")

Metal foil

“Becquerel rays” are “ionizing”

“Parallel-plate condenser"
A connection with electricity

Leyden jar ("Cylindrical condenser")

Metal foil

"Becquerel rays" are "ionizing"

"Parallel-plate condenser"
A connection with electricity

Leyden jar
("Cylindrical condenser")

Becquerel rays gradually discharge the condenser

Very small! Need very precise experiments!
How to charge the condenser?

“Parallel-plate condenser”

“Piezoelectric crystal”
How to measure the discharge?

Electrometer
*(Needs to be very sensitive!)*
How to perform the experiment?

Electrometer
*(Needs to be very sensitive!)*
How to perform the experiment?

1) Put material sample into parallel-plate condenser

Electrometer
(Needs to be very sensitive!)
How to perform the experiment?

1) Put material sample into parallel-plate condenser
2) Wait until discharging condenser reaches specified level

Electrometer
(Needs to be very sensitive!)
How to perform the experiment?

1) Put material sample into parallel-plate condenser

2) Wait until discharging condenser reaches specified level

Electrometer
(Needs to be very sensitive!)
How to perform the experiment?

1) Put material sample into parallel-plate condenser

2) Wait until discharging condenser reaches specified level

Electrometer
(Needs to be very sensitive!)
How to perform the experiment?

1) Put material sample into parallel-plate condenser
2) Wait until discharging condenser reaches specified level

Electrometer
(Needs to be very sensitive!)
How to perform the experiment?

1) Put material sample into parallel-plate condenser
2) Wait until discharging condenser reaches specified level

Electrometer
(Needs to be very sensitive!)
How to perform the experiment?

1) Put material sample into parallel-plate condenser
2) Wait until discharging condenser reaches specified level

Electrometer
(Needs to be very sensitive!)
How to perform the experiment?

1) Put material sample into parallel-plate condenser
2) Wait until discharging condenser reaches specified level
3) Add additional weight to the piezoelectric crystal to recharge condenser to original level
   → Time interval measures strength of radiation
The real experiment
The real plate condenser
The real plate condenser
The real plate condenser

"Ionization chamber"
The real piezoelectric crystal
The real piezoelectric crystal
Pierre’s precision electrometer
Pierre’s precision electrometer
Pierre’s precision electrometer
Pierre’s precision electrometer
Pierre’s precision electrometer
Pierre’s precision electrometer
Pierre’s precision electrometer
Taking the measurements
Taking the measurements
Testing different materials

Uranium and thorium minerals are the most “active”
Testing different materials

Uranium and thorium minerals are the most “active”

“I was struck by the fact that the activity of uranium and thorium compounds appears to be an atomic property of the element uranium and of the element thorium.”
Testing different materials

Uranium and thorium minerals are the most “active”

<table>
<thead>
<tr>
<th>Material</th>
<th>Activity (Ampères)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium légèrement carburé</td>
<td>44 x 10^-19</td>
</tr>
<tr>
<td>Oxyde noir d'uranium U³O³</td>
<td>37</td>
</tr>
<tr>
<td>Oxyde vert d'uranium U²O³</td>
<td>19</td>
</tr>
<tr>
<td>Uranates d'ammonium, de potassium, de sodium, environ</td>
<td>12</td>
</tr>
<tr>
<td>Acide uranique hydraté</td>
<td>6</td>
</tr>
<tr>
<td>Azotate d'uranyle, sulfate uranieux, sulfate d'uranyle et de potassium, environ</td>
<td>7</td>
</tr>
<tr>
<td>Chalcolite artificie (phosphate de cuivre et d'uranyle)</td>
<td>9</td>
</tr>
<tr>
<td>Oxyde de thorium en couche de 0.25 d'épaisseur</td>
<td>22</td>
</tr>
<tr>
<td>Oxyde de thorium en couche de 6 mm d'épaisseur</td>
<td>53</td>
</tr>
<tr>
<td>Sulfate de thorium</td>
<td>8</td>
</tr>
<tr>
<td>Pechblende de Johanngeorgenstadt</td>
<td>83</td>
</tr>
<tr>
<td>» de Cornwallis</td>
<td>16</td>
</tr>
<tr>
<td>» de Joachimthal et de Psvran</td>
<td>67</td>
</tr>
<tr>
<td>Chalcolite naturelle</td>
<td>52</td>
</tr>
<tr>
<td>Autinite</td>
<td>27</td>
</tr>
<tr>
<td>Thorites diverses</td>
<td>14</td>
</tr>
<tr>
<td>Orangite</td>
<td>10</td>
</tr>
<tr>
<td>Samarskite</td>
<td>11</td>
</tr>
<tr>
<td>Fergusonite, monazite, xénotime, niobite, aschimate</td>
<td>de 3 à 7</td>
</tr>
<tr>
<td>Clévoite très active</td>
<td></td>
</tr>
</tbody>
</table>

“I was struck by the fact that the activity of uranium and thorium compounds appears to be an atomic property of the element uranium and of the element thorium.”

“The activity is not destroyed by either physical changes of state or chemical transformations.”
Testing different materials

Uranium and thorium minerals are the most “active”

<table>
<thead>
<tr>
<th>Material Description</th>
<th>amps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium légèrement carburé</td>
<td>$24 \times 10^{-12}$</td>
</tr>
<tr>
<td>Oxyde noir d’uranium $U_3O_4$</td>
<td>$37 \mu$</td>
</tr>
<tr>
<td>Oxyde vert d’uranium $U_3O_4$</td>
<td>$18 \mu$</td>
</tr>
<tr>
<td>Uranates d’ammonium, de potassium, de sodium, environ</td>
<td>$12 \mu$</td>
</tr>
<tr>
<td>Acide uranique hydraté</td>
<td>$6 \mu$</td>
</tr>
<tr>
<td>Azotate d’uranyle, sulfate uraneux, sulfate d’uranyle et de potassium, environ</td>
<td>$7 \mu$</td>
</tr>
<tr>
<td>Chalcolite artificielle (phosphate de cuivre et d’uranyle)</td>
<td>$9 \mu$</td>
</tr>
<tr>
<td>Oxyde de thorium en couche de 6 mm d’épaisseur</td>
<td>$22 \mu$</td>
</tr>
<tr>
<td>Oxyde de thorium en couche de 6 mm d’épaisseur</td>
<td>$33 \mu$</td>
</tr>
<tr>
<td>Sulfate de thorium</td>
<td>$8 \mu$</td>
</tr>
<tr>
<td>Pechblende de Johanngeorgenstadt</td>
<td>$83 \mu$</td>
</tr>
<tr>
<td>» de Cornwallis</td>
<td>$16 \mu$</td>
</tr>
<tr>
<td>» de Joachimsthal et de Psbran</td>
<td>$67 \mu$</td>
</tr>
<tr>
<td>Chalcolite naturelle</td>
<td>$52 \mu$</td>
</tr>
<tr>
<td>Autunite</td>
<td>$27 \mu$</td>
</tr>
<tr>
<td>Thorites diverses</td>
<td>de 2 à $14 \mu$</td>
</tr>
<tr>
<td>Orangite</td>
<td>$20 \mu$</td>
</tr>
<tr>
<td>Samarskite</td>
<td>$11 \mu$</td>
</tr>
<tr>
<td>Fergussonite, monazite, xénotime, niobite, aschlanite</td>
<td>de 3 à $7 \mu$</td>
</tr>
<tr>
<td>Clévote très active</td>
<td></td>
</tr>
</tbody>
</table>
Testing different materials

Uranium and thorium minerals are the most “active”

“Two minerals of uranium, pitchblende and chalcolite are much more active than uranium itself.”
Testing different materials

Uranium and thorium minerals are the most “active”

<table>
<thead>
<tr>
<th>Material</th>
<th>Activity (Ampères)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium légèrement carburé</td>
<td>$34 \times 10^{-8}$</td>
</tr>
<tr>
<td>Oxyde noir d’uranium $\text{U}_3\text{O}_4$</td>
<td>37</td>
</tr>
<tr>
<td>Oxyde vert d’uranium $\text{U}_3\text{O}_4$</td>
<td>18</td>
</tr>
<tr>
<td>Uranates d’ammonium, de potassium, de sodium, environ</td>
<td>12</td>
</tr>
<tr>
<td>Acide uranique hydraté</td>
<td>6</td>
</tr>
<tr>
<td>Azotate d’uranyle, sulfate uraneux, sulfate d’uranyle et de potassium,</td>
<td>7</td>
</tr>
<tr>
<td>environ</td>
<td></td>
</tr>
<tr>
<td>Chalcolite artificielle (phosphate de cuivre et d’uranyle)</td>
<td>9</td>
</tr>
<tr>
<td>Oxyde de thorium en couche de 0mm, 25 d’épaisseur</td>
<td>22</td>
</tr>
<tr>
<td>Oxyde de thorium en couche de 6mm d’épaisseur</td>
<td>53</td>
</tr>
<tr>
<td>Sulfate de thorium</td>
<td>8</td>
</tr>
<tr>
<td>Pechblende de Johanngeorgenstadt</td>
<td>83</td>
</tr>
<tr>
<td>» de Cornwallis</td>
<td>16</td>
</tr>
<tr>
<td>» de Joachimsthal et de Paibran</td>
<td>67</td>
</tr>
<tr>
<td>Chalcolite naturelle</td>
<td>53</td>
</tr>
<tr>
<td>Autunite</td>
<td>27</td>
</tr>
<tr>
<td>Thorites diverses</td>
<td>de 2 à 14</td>
</tr>
<tr>
<td>Orangite</td>
<td>16</td>
</tr>
<tr>
<td>Samarskite</td>
<td>11</td>
</tr>
<tr>
<td>Fergusonite, monazite, xenotime, niobite, aschwinite</td>
<td>de 3 à 7</td>
</tr>
<tr>
<td>Clévètè très active</td>
<td></td>
</tr>
</tbody>
</table>

“The fact is very remarkable, and leads to the belief that these minerals may contain an element which is much more active than uranium.”
Testing different materials

Uranium and thorium minerals are the most “active”

“The fact is very remarkable, and leads to the belief that these minerals may contain an element which is much more active than uranium.”
The fact is very remarkable, and leads to the belief that these minerals may contain an element which is much more active than uranium.

→ “Radioactive” materials
Is there more than uranium?

“We have sought to isolate this substance in pitchblende and experiment has just confirmed the preceding conjectures.”
Is there more than uranium?

“We have sought to isolate this substance in pitchblende and experiment has just confirmed the preceding conjectures.”

“We have treated it with acids and have treated the solutions obtained with hydrogen sulfide.”
Is there more than uranium?

“We have sought to isolate this substance in pitchblende and experiment has just confirmed the preceding conjectures.”

“We have treated it with acids and have treated the solutions obtained with hydrogen sulfide.”

“We believe therefore that the substance which we have removed from pitchblende contains a metal not yet reported close to bismuth in its analytical properties.”
Is there more than uranium?

“We have sought to isolate this substance in pitchblende and experiment has just confirmed the preceding conjectures.”

“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.”

“We believe therefore that the substance which we have removed from pitchblende contains a metal not yet reported close to bismuth in its analytical properties.”

“We have treated it with acids and have treated the solutions obtained with hydrogen sulfide.”
Is there more than uranium?

“We have sought to isolate this substance in pitchblende and experiment has just confirmed the preceding conjectures.”

“We have treated it with acids and have treated the solutions obtained with hydrogen sulfide.”

“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.”

“We have treated it with acids and have treated the solutions obtained with hydrogen sulfide.”
Something else?
“In the course of these researches we have found a second substance strongly radioactive and entirely different in its chemical properties from Polonium.”
“In the course of these researches we have found a second substance strongly radioactive and entirely different in its chemical properties from Polonium.”

“We believe that the new radioactive substance contains a new element to which we propose to give the name radium.”
“In the course of these researches we have found a second substance strongly radioactive and entirely different in its chemical properties from Polonium.”

“We believe that the new radioactive substance contains a new element to which we propose to give the name radium.”
“In the course of these researches we have found a second substance strongly radioactive and entirely different in its chemical properties from Polonium.”

“We believe that the new radioactive substance contains a new element to which we propose to give the name radium.”

“Sometimes I had to spend a whole day stirring a boiling mass with a heavy iron rod nearly as big as myself. I would be broken with fatigue at day’s end.”
Ernest Rutherford
Ernest Rutherford

Nelson, New Zealand
Ernest Rutherford

Nelson, New Zealand

His ticket overseas

-European and Other Foreign Items-

London, July 11

The Commissioners of the 1851 Exhibition have awarded the science research scholarships to Ernest Rutherford, of New Zealand, and Alexander Watt, of the Sydney University.
Ernest Rutherford

Nelson, New Zealand

His ticket overseas

At the Cavendish with other “aliens”
Ernest Rutherford

Nelson, New Zealand

At the Cavendish with other “aliens”

His ticket overseas

McGill University, Montreal

“Rejoice with me, my dear girl, for matrimony is looming in the distance.”
How penetrating are the rays?

Radiation measurement in the “Curie method”:

Parallel-plate condenser

Battery

Electrometer

Uranium

Earth
How penetrating are the rays?

Radiation measurement in the “Curie method”:

How many sheets are needed to absorb ("shield") the radiation?
How penetrating are the rays?

Radiation measurement in the “Curie method”:

How many sheets are needed to absorb ("shield") the radiation?
How penetrating are the rays?

Radiation measurement in the “Curie method”:

- Parallel-plate condenser
- Thin aluminum sheets
- Battery
- Electrometer

How many sheets are needed to absorb (“shield”) the radiation?
How penetrating are the rays?

Radiation measurement in the “Curie method”:

Parallel-plate condenser

Thin aluminum sheets

Battery

Electrometer

How many sheets are needed to absorb ("shield") the radiation?
How penetrating are the rays?

Radiation measurement in the “Curie method”:

- **Parallel-plate condenser**
- **Thin aluminum sheets**
- **Battery**
- **Electrometer**

How many sheets are needed to absorb (“**shield**”) the radiation?
How penetrating are the rays?

Radiation measurement in the “Curie method”:

Parallel-plate condenser

Thin aluminum sheets

Battery

Electrometer

How many sheets are needed to absorb (“shield”) the radiation?
Only one kind of rays?

“The aluminium foil in this case was about 0.0005 cm thick.”
Only one kind of rays?

“[The aluminium foil in this case was about 0.0005 cm thick.].”
Only one kind of rays?

“The aluminium foil in this case was about 0.0005 cm thick.”
More than one kind of rays!

“These experiments show that the uranium radiation is complex and that there are present at least two distinct types of radiation.”
More than one kind of rays!

“These experiments show that the uranium radiation is complex and that there are present at least two distinct types of radiation.”
More than one kind of rays!

“These experiments show that the uranium radiation is complex and that there are present at least two distinct types of radiation.”
More than one kind of rays!

“These experiments show that the uranium radiation is complex and that there are present at least two distinct types of radiation.”
More than one kind of rays!

“These experiments show that the uranium radiation is complex and that there are present at least two distinct types of radiation.”
More than one kind of rays!

“These experiments show that the uranium radiation is complex and that there are present at least two distinct types of radiation.”
More than one kind of rays!

“One that is very readily absorbed, which will be termed for convenience the $\alpha$ radiation …”

“These experiments show that the uranium radiation is complex and that there are present at least two distinct types of radiation.”
More than one kind of rays!

“One that is very readily absorbed, which will be termed for convenience the $\alpha$ radiation …”

“… and the other of a more penetrating character, which will be termed the $\beta$ radiation.

“These experiments show that the uranium radiation is complex and that there are present at least two distinct types of radiation.”
What are $\alpha$ rays made of?
What are $\alpha$ rays made of?

Just like Thomson’s experiment
What are $\alpha$ rays made of?

Just like Thomson’s experiment
What are \( \alpha \) rays made of?

Just like Thomson’s experiment

Radium as \( \alpha \)-radiation source
What are $\alpha$ rays made of?

Just like Thomson’s experiment

Radium as $\alpha$-radiation source
What are $\alpha$ rays made of?

Just like Thomson’s experiment

Radium as $\alpha$-radiation source
What are $\alpha$ rays made of?

Ionization chamber

Radium as $\alpha$-radiation source
What are \( \alpha \) rays made of?

“The direction of deviation in a magnetic field was **opposite in sense to the cathode rays**, i.e. the \( \alpha \) rays consisted of **positively charged particles**.”
What are $\alpha$ rays made of?

“The direction of deviation in a magnetic field was opposite in sense to the cathode rays, i.e. the $\alpha$ rays consisted of positively charged particles.”
What are $\alpha$ rays made of?

“With the largest electromagnet in the laboratory, I was only able to deviate about 30 per cent of the $\alpha$ rays.”

“I was, however, enabled to make use of the field magnet of a 30 kilowatt Edison dynamo.”

“The direction of deviation in a magnetic field was opposite in sense to the cathode rays, i.e. the $\alpha$ rays consisted of positively charged particles.”
What are $\alpha$ rays made of?

“With the largest electromagnet in the laboratory, I was only able to deviate about 30 per cent of the $\alpha$ rays.”

“I was, however, enabled to make use of the field magnet of a 30 kilowatt Edison dynamo.”

Radium already used as a tool for research!

“The direction of deviation in a magnetic field was opposite in sense to the cathode rays, i.e. the $\alpha$ rays consisted of positively charged particles.”
What are $\alpha$ rays made of?

“With the largest electromagnet in the laboratory, I was only able to deviate about 30 per cent of the $\alpha$ rays.”

“I was, however, enabled to make use of the field magnet of a 30 kilowatt Edison dynamo.”

Radium already used as a tool for research!

“The sample of radium of greater activity than that normally sold was obtained through the kindness of M. Curie”

“The direction of deviation in a magnetic field was opposite in sense to the cathode rays, i.e. the $\alpha$ rays consisted of positively charged particles.”
1903: Three kinds of radioactivity
1903: Three kinds of radioactivity

$\alpha$

Positively charged

high $m/e$

easily stopped
1903: Three kinds of radioactivity

$\alpha$
- Positively charged
- High $m/e$
- Easily stopped

$\beta$
- Negatively charged
- Small $m/e$
- More penetrating
1903: Three kinds of radioactivity

\[ \alpha \]
- Positively charged
- High \( m/e \)
- Easily stopped

\[ \beta \]
- Negatively charged
- Small \( m/e \)
- More penetrating

\[ \gamma \]
- Uncharged
- Even more penetrating
1903: Three kinds of radioactivity

- **α** Positively charged
  - high $m/e$
  - easily stopped

- **β** Negatively charged
  - small $m/e$
  - more penetrating

- **γ** Uncharged
  - even more penetrating

Paul Villard
Chemist and Physicist in Paris
Moving to Manchester

An offer he could not refuse ...
Moving to Manchester

An offer he could not refuse ...
Moving to Manchester

An offer he could not refuse ...
Moving to Manchester

An offer he could not refuse ...
Moving to Manchester

An offer he could not refuse ...

“Everybody seems jolly & anxious to help and I find a most enjoyable absence of convention.”
Moving to Manchester

An offer he could not refuse ...

“Everybody seems jolly & anxious to help and I find a most enjoyable absence of convention.”

“I find the students here regard a professor as little short of Lord God Almighty. It is quite refreshing after the critical attitude of the Canadian students.”
New instruments
New instruments

Ionization chamber
New instruments

Ionization chamber

The first particle counter
(Rutherford and Geiger)

An Electrical Method of Counting the Number of α-Particles from Radio-active Substances.

By E. Rutherford, F.R.S., Professor of Physics, and H. Geiger, Ph.D.,
John Harling Fellow, University of Manchester.

(Read June 18; MS. received July 17, 1908.)
New instruments

Ionization chamber

The first particle counter
(Rutherford and Geiger)

An Electrical Method of Counting the Number of α-Particles from Radio-active Substances.

By E. Rutherford, F.R.S., Professor of Physics, and H. Geiger, Ph.D., John Harling Fellow, University of Manchester.

(Read June 18; MS. received July 17, 1908.)
New instruments

Ionization chamber

The first particle counter
(Rutherford and Geiger)

"Amplification"

An Electrical Method of Counting the Number of α-Particles from Radio-active Substances.

By E. Rutherford, F.R.S., Professor of Physics, and H. Geiger, Ph.D.,
John Harling Fellow, University of Manchester.

(Read June 18; MS. received July 17, 1908.)
New instruments

Ionization chamber

The first particle counter
(Rutherford and Geiger)

"Amplification"

An Electrical Method of Counting the Number of α-Particles from Radio-active Substances.

By E. Rutherford, F.R.S., Professor of Physics, and H. Geiger, Ph.D.,
John Harling Fellow, University of Manchester.

(Read June 18; MS. received July 17, 1908.)
New instruments

Ionization chamber

The first particle counter
(Rutherford and Geiger)

"Amplification"

An Electrical Method of Counting the Number of α-Particles from Radio-active Substances.

By E. Rutherford, F.R.S., Professor of Physics, and H. Geiger, Ph.D.,
John Harling Fellow, University of Manchester.

(Read June 18; MS. received July 17, 1908.)
Anomalous scattering?

1909

Scattering through wide angle is possible!
Anomalous scattering?

1913
Anomalous scattering?

1913

Radioactive source

Thin gold foil

Fluorescent screen

Detecting Vessel

α
Anomalous scattering?

“It was quite the most incredible event that has ever happened to me in my life.”

“It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.”
The atom has a nucleus!
The atom has a nucleus!

J.J. Thomson’s “Plum pudding model”
The atom has a nucleus!

J.J. Thomson’s “Plum pudding model”
The atom has a nucleus!

J.J. Thomson’s “Plum pudding model”

Rutherford’s model of the atom
The atom has a nucleus!

J.J. Thomson’s “Plum pudding model”

Rutherford’s model of the atom
The atom has a nucleus!

J.J. Thomson’s “Plum pudding model”

Rutherford’s model of the atom
The atom has a nucleus!

J.J. Thomson's "Plum pudding model"

Rutherford's model of the atom

Rutherford's calculations describing the scattering
1914: WW1 interrupts science
1914: WW1 interrupts science

Marie Curie: invests Nobel prize money in war bonds, organizes a mobile X-ray service along the front
1914: WW1 interrupts science

Marie Curie:
invests Nobel prize money in war bonds, organizes a mobile X-ray service along the front

Rutherford and Thomson:
Serve on the Admiralty physics board
What is the nucleus made of?

**Rutherford:** “α particles can collide with the nucleus of a hydrogen atom”
What is the nucleus made of?

Rutherford: “α particles can collide with the nucleus of a hydrogen atom”
What is the nucleus made of?

Rutherford: “α particles can collide with the nucleus of a hydrogen atom”
What is the nucleus made of?

**Rutherford:** “α particles can collide with the nucleus of a hydrogen atom”

“In an end-on collision, the H-particle will have about four times the range of the α-particle producing it.”
Hydrogen contained in nitrogen?

April 1919

Nitrogen atom

Electrons

H-particles

“Liberated H-particle”

Hydrogen atom
Hydrogen contained in nitrogen?

April 1919

“We must conclude that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus.”
Hydrogen contained in nitrogen?

April 1919

“Considering the enormous intensity of the forces brought into play, it is not so much a matter of surprise that the nitrogen atom should suffer disintegration.”

“We must conclude that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus.”
Hydrogen contained in nitrogen?

April 1919

“Considering the enormous intensity of the forces brought into play, it is not so much a matter of surprise that the nitrogen atom should suffer disintegration.”

The nucleus of a hydrogen atom is a particle of its own!

“We must conclude that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus.”
“Nuclear chemistry”

Atoms are not “elementary”, they have their own building blocks!

Adding more and more electrons (and protons) builds up the elements in the periodic table.
“Nuclear chemistry”

Atoms are not “elementary”, they have their own building blocks!

Adding more and more electrons (and protons) builds up the elements in the periodic table.

Nitrogen
(Heavier than hydrogen)

Hydrogen
Atoms are not "elementary", they have their own building blocks!

Adding more and more electrons (and protons) builds up the elements in the periodic table.
“Nuclear chemistry”

Atoms are not “elementary”, they have their own building blocks!

Adding more and more electrons (and protons) builds up the elements in the periodic table.
Another hint from chemistry

Can chemical elements exist “multiple times”?

\[ \text{Th} \rightarrow \alpha \rightarrow \text{Pa} \rightarrow \beta \rightarrow \text{U} \rightarrow \beta \rightarrow \text{Np} \]

\[ \text{Uranium} \rightarrow \alpha \rightarrow \text{Thorium} \rightarrow \beta \rightarrow \text{Protactinium} \rightarrow \beta \rightarrow \text{Uranium} \]

Frederick Soddy
Another hint from chemistry

Can chemical elements exist “multiple times”?

Uranium
\[\alpha\] Thorium
\[\beta\] Protactinium
\[\beta\] Uranium

Francis Aston

Frederick Soddy
Another hint from chemistry

Can chemical elements exist “multiple times”?

α

90 Th 91 Pa 92 U 93 Np
Thorium Protactinium Uranium Neptunium

β β

Uranium

Two different “kinds” of neon with different masses!?  

Francis Aston

One of the first “mass-spectrometers” (ca. 1920)
Another hint from chemistry

Can chemical elements exist “multiple times”?

- Thorium (Th)
- Protactinium (Pa)
- Uranium (U)
- Neptunium (Np)

α

β

β

Uranium

Two different “kinds” of neon with different masses!?

Francis Aston

One of the first “mass-spectrometers” (ca. 1920)
How is this possible?

Proton

Electron
How is this possible?

But: adding another proton + electron turns it into a different (heavier) element …
How is this possible?

But: adding another proton + electron turns it into a different (heavier) element …

… not into a heavier version of the same element!
How is this possible?

But: adding another proton + electron turns it into a different (heavier) element … … not into a heavier version of the same element!

What’s wrong?
How is this possible?

But: adding another proton + electron turns it into a different (heavier) element … not into a heavier version of the same element!

What’s wrong?

Are there additional electrons in the nucleus?
A new neutral particle?

1932
A new neutral particle?

1932

James Chadwick
A new neutral particle?

1932

James Chadwick

Frédéric and Irène Joliot-Curie
A new particle?

1932

Polonium $\alpha$-source

Beryllium foil

$\alpha$

Ionization chamber

?!
A new particle?

1932

Polonium $\alpha$-source

Beryllium foil

Lead

Ionization chamber

$\alpha$
A new particle?

1932

“… remained the same even when as much as 2 cm of lead were inserted …”

→ very penetrating radiation
A new particle?

1932

“In order to explain the great penetrating power of the radiation we must assume that the particle has no net charge.”

“... remained the same even when as much as 2 cm of lead were inserted ...”

→ very penetrating radiation
“In order to explain the great penetrating power of the radiation we must assume that the particle has no net charge.”

“... remained the same even when as much as 2 cm of lead were inserted ...”

→ very penetrating radiation
Which kind of neutral particle?

Chadwick (1932):
“It is concluded that the radiation consists of neutrons, particles of mass 1, and charge 0.”

But what kind of neutron?

Proton and electron tightly bound together

New particle without building blocks

(The Joliot-Curies missed a major discovery!)
Which kind of neutral particle?

Chadwick (1932):
“It is concluded that the radiation consists of neutrons, particles of mass 1, and charge 0.”

But what kind of neutron?

Chadwick + Goldhaber (1935):
Mass of neutron larger than proton and electron taken together!

(The Joliot-Curies missed a major discovery!)
Which kind of neutral particle?

Chadwick (1932):
“It is concluded that the radiation consists of neutrons, particles of mass 1, and charge 0.”

But what kind of neutron?

Chadwick + Goldhaber (1935):
Mass of neutron larger than proton and electron taken together!

(The Joliot-Curies missed a major discovery!)
An updated view of the atom

Nitrogen
(Heavier than hydrogen)

Hydrogen

Proton
Neutron
Electron
An updated view of the atom

Nitrogen
(Heavier than hydrogen)

Hydrogen

Soddy’s “different kinds of uranium” contain different numbers of neutrons!
Dalton, 1808:

“The atoms of such bodies are conceived at present to be simple.”
Dalton, 1808:

“The atoms of such bodies are conceived at present to be simple.”

1935:

Atoms are everything but simple!

---

Elements

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>🗳️</td>
<td>🗳️</td>
<td>🗳️</td>
<td>🗳️</td>
<td>🗳️</td>
<td>🗳️</td>
<td>🗳️</td>
<td>🗳️</td>
</tr>
<tr>
<td>🗳️</td>
<td>🗳️</td>
<td>🗳️</td>
<td>🗳️</td>
<td>🗳️</td>
<td>🗳️</td>
<td>🗳️</td>
<td>🗳️</td>
</tr>
</tbody>
</table>

Plate 3

Proton

Neutron

Electron
Dalton, 1808:
“The atoms of such bodies are conceived at present to be simple.”

1935:
Atoms are everything but simple!

And again, changes in our worldview are going to have big consequences ...
Dalton, 1808:
“The atoms of such bodies are conceived at present to be simple.”

1935:
Atoms are everything but simple!

And again, changes in our worldview are going to have big consequences ... 

... next time!
HOW FUNDAMENTAL SCIENCE HAS CHANGED THE WORLD
A STORY OF INVENTION AND DISCOVERY