# The Development of Scientific Thought in the 20th Century

<table>
<thead>
<tr>
<th>Event</th>
<th>Year</th>
<th>Inventor/Contributor</th>
</tr>
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<tr>
<td>Discovery &amp; study of radioactivity</td>
<td>1898</td>
<td>Marie &amp;.Pierre Curie</td>
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<tr>
<td>Introduction of quantum concept</td>
<td>1900</td>
<td>Max Planck $h$</td>
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<td>Theory of special relativity</td>
<td>1905</td>
<td>Albert Einstein $E=mc^2$</td>
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<tr>
<td>Quantization of light (photoelectric effect)</td>
<td>1905</td>
<td>Albert Einstein $E=\hbar \nu$</td>
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<td>Discovery of atomic nucleus</td>
<td>1911</td>
<td>Ernest Rutherford</td>
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<td>Interpretation of atom structure</td>
<td>1913</td>
<td>Nils Bohr</td>
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<td>Particle waves</td>
<td>1924</td>
<td>Louis de Broglie</td>
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<td>Wave mechanics</td>
<td>1925</td>
<td>Erwin Schrödinger</td>
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<td>Uncertainty principle</td>
<td>1927</td>
<td>Werner Heisenberg</td>
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<td>Discovery of Neutron</td>
<td>1932</td>
<td>James Chadwick</td>
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<td>Artificial Radioactivity (Reactions)</td>
<td>1934</td>
<td>Frederic Joliot &amp; Irene Curie</td>
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<tr>
<td>Discovery of fission</td>
<td>1938</td>
<td>Otto Hahn, Fritz Strassmann</td>
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<tr>
<td>Interpretation of fission</td>
<td>1938</td>
<td>Liese Meitner, Otto Frisch</td>
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<td>Prediction of thermonuclear fusion</td>
<td>1939</td>
<td>C.F. v. Weizsäcker, H. Bethe</td>
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The new radiating material

Radioactive material such as Uranium - first discovered by Henri Becquerel – was studied extensively by Marie and Pierre Curie. They discovered other natural radioactive elements such as Radium and Polonium.

Nobel Prize 1903 and 1911!

Unit of radioactivity:

The activity of 1g Ra = 1Ci = \(3.7 \times 10^{10}\) decays/s   1Bq = 1 decay/s

Discovery triggered a unbounded enthusiasm and led to a large number of medical and industrial applications
Applications for Radioactivity
Applications

Popular products included radioactive toothpaste for cleaner teeth and better digestion, face cream to lighten the skin; radioactive hair tonic, suppositories, and radium-laced chocolate bars marketed in Germany as a "rejuvenator." In the U.S, hundreds of thousands of people began drinking bottled water laced with radium, as a general elixir known popularly as "liquid sunshine." As recently as 1952 LIFE magazine wrote about the beneficial effects of inhaling radioactive radon gas in deep mines. As late as 1953, a company in Denver was promoting a radium-based contraceptive jelly.
Radium Dials

Increase in cancer (tongue – bone) due to extensive radium exposure

According to a Department of Commerce Information Circular from 1930, the radium paint might contain "from 0.7 to 3 and even 4 milligrams of radium"; this corresponds to a radioactivity level of 0.7 to 4 mCi or 26-150 GBq in modern units.
Explanation of natural radioactivity

Radioactivity comes in three forms $\alpha$, $\beta$, $\gamma$

Ernest Rutherford's picture of transmutation. A radium atom emits an alpha particle, turning into “Emanation” (in fact the gas radon). This atom in turn emits a particle to become “Radium A” (now known to be a form of polonium). The chain eventually ends with stable lead.

*Philosophical Transactions of the Royal Society of London*, 1905.
The radioactive decay law

\[ A_{\text{mother}}(t) = A_0 \cdot e^{-\lambda t} \]

\[ A_{\text{daughter}}(t) = A_0 \cdot (1 - e^{-\lambda t}) \]

\( \lambda \) = decay constant; a natural constant for each radioactive element.
Half life: \( t_{1/2} = \ln 2 / \lambda \)

exponential decay with time!
1\textsuperscript{st} example: $^{22}\text{Na}$

$^{22}\text{Na}$ has a half-life of 2.6 years, what is the decay constant? Mass number $A=22$; *(don't confuse with activity $A(t)$!)*

\[
\lambda = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{2.6 \text{ yr}} = 0.27 \text{ yr}^{-1}:
\]

\[
1 \text{ yr} = 3.14 \cdot 10^7 \text{ s} \approx \pi \cdot 10^7 \text{ s}
\]

\[
\lambda = \frac{\ln 2}{2.6 \cdot 3.14 \cdot 10^7 \text{ s}} = 8.5 \cdot 10^{-9} \text{ s}^{-1}
\]
radioactive decay laws

Activity of radioactive substance $A(t)$ is at any time $t$ proportional to number of radioactive particles $N(t)$:

$$A(t) = \lambda \cdot N(t)$$

A $^{22}$Na source has an activity of $1 \, \mu\text{Ci} = 10^{-6} \, \text{Ci}$, how many $^{22}$Na isotopes are contained in the source?

(1 Ci = $3.7 \cdot 10^{10}$ decays/s)

$$N = \frac{A}{\lambda} = \frac{10^{-6} \, \text{Ci}}{8.5 \cdot 10^{-9} \, \text{s}^{-1}} = \frac{10^{-6} \cdot 3.7 \cdot 10^{10}}{8.5 \cdot 10^{-9} \, \text{s}^{-1}} = 4.36 \cdot 10^{12}$$
How many grams of $^{22}\text{Na}$ are in the source?

A gram of isotope with mass number $A$ contains $N_A$ isotopes

$$N_A \equiv \text{Avogadro’s Number} = 6.023 \cdot 10^{23}$$

$\Rightarrow$ 22g of $^{22}\text{Na}$ contains $6.023 \cdot 10^{23}$ isotopes

$$N = 4.36 \cdot 10^{12} \text{ particles}$$

$$1g = \frac{6.023 \cdot 10^{23}}{22} \text{ particles}$$

$$N = \frac{22 \cdot 4.36 \cdot 10^{12}}{6.023 \cdot 10^{23}} g = 1.59 \cdot 10^{-10} g$$
\[ N(t) = N_0 \cdot e^{-\lambda \cdot t} \]

How many particles are in the source after 1 y, 2 y, 20 y?

\[ N(t) = 4.36 \cdot 10^{12} \cdot e^{-0.27 \text{y}^{-1} \cdot t} \]
\[ A(t) = \lambda \cdot N(t) = 8.5 \cdot 10^{-9} \text{s}^{-1} \cdot N(t) \]

\[ N(1\text{y}) = 4.36 \cdot 10^{12} \cdot e^{-0.27 \text{y}^{-1} \cdot 1\text{y}} = 3.33 \cdot 10^{12} \]
\[ A(1\text{y}) = 28305 \text{s}^{-1} = 0.765 \mu\text{Ci} \]

\[ N(2\text{y}) = 4.36 \cdot 10^{12} \cdot e^{-0.27 \text{y}^{-1} \cdot 2\text{y}} = 2.54 \cdot 10^{12} \]
\[ A(2\text{y}) = 21590 \text{s}^{-1} = 0.58 \mu\text{Ci} \]

\[ N(10\text{y}) = 4.36 \cdot 10^{12} \cdot e^{-0.27 \text{y}^{-1} \cdot 10\text{y}} = 2.93 \cdot 10^{11} \]
\[ A(10\text{y}) = 2490.5 \text{s}^{-1} = 0.067 \mu\text{Ci} \]

Decay in particle number and corresponding activity!
2\textsuperscript{nd} example: Radioactive Decay

Plutonium $^{239}\text{Pu}$, has a half life of 24,360 years.

1. What is the decay constant?

2. How much of 1kg $^{239}\text{Pu}$ is left after 100 years?

\[ \lambda = \frac{\ln 2}{t_{1/2}} = \frac{\ln 2}{24360\, \text{y}} = 2.85 \cdot 10^{-5}\, \text{y}^{-1} \]

\[ N_{^{239}\text{Pu}}(t) = N_0 \cdot e^{-\lambda \cdot t} \Rightarrow N_{^{239}\text{Pu}}(100\, \text{y}) = 1\, \text{kg} \cdot e^{-2.85 \cdot 10^{-5}\, \text{y}^{-1} \cdot 100\, \text{y}} \]

\[ N_{^{239}\text{Pu}}(100\, \text{y}) = 0.9972\, \text{kg} \]

\[ N_{^{239}\text{Pu}}(1,000\, \text{y}) = 0.9719\, \text{kg} \]

\[ N_{^{239}\text{Pu}}(10,000\, \text{y}) = 0.7520\, \text{kg} \]

\[ N_{^{239}\text{Pu}}(24,360\, \text{y}) = 0.5\, \text{kg} \]

\[ N_{^{239}\text{Pu}}(100,000\, \text{y}) = 0.0578\, \text{kg} \]
The first step: $E=mc^2$

"It followed from the special theory of relativity that mass and energy are both but different manifestations of the same thing - a somewhat unfamiliar conception for the average mind. Furthermore, the equation $E$ is equal to $mc^2$, in which energy is put equal to mass, multiplied by the square of the velocity of light, showed that very small amounts of mass may be converted into a very large amount of energy and vice versa. The mass and energy were in fact equivalent, according to the formula mentioned before. This was demonstrated by Cockcroft and Walton in 1932, experimentally."

Albert Einstein

Nobel Prize 1921
Example: Mass-Energy

\[ E = mc^2 \]

\[ 1 \, J = 1 \, kg \left( \frac{m}{s} \right)^2 \]

\[ c = 3 \cdot 10^8 \frac{m}{s} \]

1 kg of matter corresponds to an energy of:

\[ E = 1 \, kg \cdot (3 \cdot 10^8 \, m/s)^2 = 9 \cdot 10^{16} \, kg \left( \frac{m}{s} \right)^2 = 9 \cdot 10^{16} \, J \]

Definition: 1 ton of TNT = 4.184 x 10^9 joule (J).

1 kg (2.2 lb) of matter converted completely into energy would be equivalent to the energy released by exploding 22 megatons of TNT.

Nuclear physics units: \[ 1 \, eV = 1.6 \cdot 10^{-19} \, J \]

1 electron-volt is the energy one electron picks up if accelerated in an electrical potential of one Volt.
The discovery of the neutron

By 1932 nucleus was thought to consist of protons and electrons which were emitted in $\beta$-decay. New Chadwick’s experiment revealed a third particle, the neutron

Strong Polonium source emitted $\alpha$ particles which bombarded Be; radiation was emitted which – based on energy and momentum transfer arguments - could only be neutral particles with similar mass as protons $\Rightarrow$ neutrons: BEGIN OF NUCLEAR PHYSICS!
The model of the nucleus

Nucleus with Z protons (p) and N neutrons (n) with a total mass number \( A = Z + N \)

Hydrogen: 1 p, 0,1 n  
\[ ^1_1H_0 \quad ^2_1D_1 \]

Helium: 2 p, 1,2 n  
\[ ^3_2He_1 \quad ^4_2He_2 \]

Lithium: 3 p, 3,4 n  
\[ ^6_3Li_3 \quad ^7_3Li_4 \]

Carbon: 6 p, 6,7 n  
\[ ^{12}_6C_6 \quad ^{13}_6C_7 \]

Uranium: 92 p, 143,146 n  
\[ ^{235}_{92}U_{143} \quad ^{238}_{92}U_{146} \]
Modern Picture nuclide chart

- **Z=8, O isotopes**
- **A=20 isobars**
- **N=12 isotones**

**Isotopes:** Z=constant, N varies!
**Isotones:** N=constant, Z varies!
**Isobars:** A=constant, Z,N varies!
## Energy in Nuclei

According to Einstein’s formula each nucleus with certain mass $m$ stores energy $E=mc^2$

<table>
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<tr>
<th>Nucleus</th>
<th>Mass (g)</th>
<th>Binding Energy (J)</th>
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<tbody>
<tr>
<td>Proton</td>
<td>$m_p = 1.007596 \cdot 1.66 \cdot 10^{-24}$</td>
<td>$B(12C) = 1.47 \cdot 10^{-11}$; $B/A = 1.23 \cdot 10^{-12}$</td>
</tr>
<tr>
<td>Neutron</td>
<td>$m_n = 1.008486 \cdot 1.66 \cdot 10^{-24}$</td>
<td>$B(238U) = 2.64 \cdot 10^{-10}$; $B/A = 1.21 \cdot 10^{-12}$</td>
</tr>
<tr>
<td>Carbon</td>
<td>$m_{12C} = 12.00000 \cdot 1.66 \cdot 10^{-24}$</td>
<td>$B/A = 1.23 \cdot 10^{-12}$</td>
</tr>
<tr>
<td>Uranium</td>
<td>$m_{238U} = 238.050783 \cdot 1.66 \cdot 10^{-24}$</td>
<td>$B/A = 1.21 \cdot 10^{-12}$</td>
</tr>
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</table>

1 amu = 1/12($M^{12C}$) = 1.66\cdot 10^{-24} g

Breaking up nuclei into their constituents requires energy
Nuclear Potential

\[ B = a_v \cdot A - a_s \cdot A^{2/3} - a_c \cdot Z \cdot (Z - 1) \cdot A^{-1/3} - a_{sym} \cdot \frac{(A - 2Z)^2}{A} + \delta \]

\[ \delta = +a_p \cdot A^{-4/3} \ (Z, N \ \text{even}); \ \delta = -a_p \cdot A^{-4/3} \ (Z, N \ \text{odd}); \ \delta = 0 \ (A = Z + N \ \text{odd}); \]

\[ a_v = 15.5\text{MeV}; \ a_s = 16.8\text{MeV}; \ a_c = 0.72\text{MeV}; \ a_{sym} = 23\text{MeV}; \ a_p = 34\text{MeV} \]

http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/liqdrop.html#c2

1 MeV = 1.602 \times 10^{-13} J
Nuclear Binding Energy

$$1 \text{ MeV} = 1.602 \cdot 10^{-13} \text{ J}$$

Binding energy normalized to mass number $B/A$
Example: Nuclear Binding Energy

Conversion of nuclei through fusion or fission leads to release of energy!

\[
\begin{align*}
{\text{^2H}}_1 + {\text{^2H}}_1 & \Rightarrow {\text{^4He}}_2 + Q \\
Q &= B({\text{^4He}}) - 2 \cdot \left( B({\text{^2H}}) + B({\text{^2H}}) \right)
\end{align*}
\]

\[
Q = 2 \cdot 3.34131 \cdot 10^{-13} \text{J} - 4.53295 \cdot 10^{-12} \text{J} = 3.8647 \cdot 10^{-12} \text{J}
\]

\[
\begin{align*}
{\text{^{238}U}}_{146} & \Rightarrow 2 \cdot {\text{^{119}Pd}}_{73} + Q \\
Q &= B({\text{^{119}Pd}}) + B({\text{^{119}Pd}}) - B({\text{^{238}U}}_{146})
\end{align*}
\]

\[
Q = 2.88631 \cdot 10^{-10} \text{J} - 2 \cdot 1.59633 \cdot 10^{-10} \text{J} = 3.06542 \cdot 10^{-11} \text{J}
\]

http://ie.lbl.gov/toimass.html
http://nucleardata.nuclear.lu.se/database/masses/
http://www.nndc.bnl.gov/masses/mass.mas03
Nuclear Energy possible through fission and fusion