Classroom notes for: Radiation and Life

98.101.201
Professor: Thomas M. Regan
Pinanski 207 ext 3283
Radiation Continued

- 1902- Rutherford and Frederick Soddy (1877-1956)
  - expanding upon the efforts of Crookes in 1900, proposed that radioactive elements, after emitting radiation, transform into other radioactive elements, which in turn transform themselves. This is the first suggestion of a radioactive series.
Rutherford and Soddy extracted an active substance from thorium. They called it thorium X. Four days after the extraction, they found that the thorium X had lost half of its activity. The original thorium had regained exactly as much activity as the thorium X had lost. Rutherford and Soddy figured out what was happening. Some atoms of thorium were spontaneously changing into atoms of thorium X. At the same time, some of the thorium X was losing its activity. The creation of new thorium X balanced the loss of activity. (http://www.xmission.com/~dparker/nucleus.html)

Going against a popularly accepted belief that elements were immutable, Rutherford showed that some heavy atoms spontaneously decay into slightly lighter, and chemically different, atoms. His book on this subject, *Radioactivity*, was published in 1904.
Decay chains

The nuclides generated during the decay of the very long-lived natural radionuclides U-238 (half-life 4.5 bn years), U-235 (half-life 0.7 bn years) and Th-232 (half-life 14 bn years) are in turn radioactive, and therefore decay again. Thus, the so-called decay chains are created which end only when a non-radioactive nuclide is formed. The uranium-radium decay chain starts from U-238 and ends via 18 intermediate states at the stable lead-206. Uranium-235 is at the beginning of the uranium-actinium decay chain leading via 15 radionuclides to lead-207. With ten intermediate states, the thorium decay chain starting with thorium-232 and ending at lead-208 is the shortest.
Rutherford, Continued

Going against a popularly accepted belief that elements were immutable, Rutherford showed that some heavy atoms spontaneously decay into slightly lighter, and chemically different, atoms. His book on this subject, *Radioactivity*, was published in 1904.

Rutherford received the Nobel Prize for Chemistry in 1908 “for his investigations into the disintegration of the elements, and the chemistry of radioactive substances”; however, his most famous contribution was yet to come.

Rutherford was from New Zealand, and helped his family on the farm by digging potatoes, among other things. He won a scholarship to Cambridge to work as a research (graduate) student under professor J. J. Thomson, and left New Zealand in 1895 at the age of 24, purportedly saying: “That’s the last potato I will ever dig.”
1911- Rutherford discovered the atom’s nucleus

He devised an ingenious experiment with fellow collaborators Marsden and Johannes Hans Wilhelm Geiger (1882-1945)- of Geiger counter fame. They used a radioactive source to shoot a collimated beam of alpha particles at an extremely thin gold foil (on the order of 1μm, or 1/25,000th to 1/50,000th of one inch thick).

Using microscopes, Marsden and Geiger counted individual flashes on a zinc sulfide coated screen to observe the number of alphas penetrating the foil.

Most of the alpha particles passed through, unaffected and undeflected, as though there were nothing there, suggesting that atoms were mostly empty space.

Even more surprisingly, some of the alpha particles were deflected, even through large angles, suggesting a makeup for the atom completely different than that proposed in the plum-pudding model.
Rutherford’s surprise was evident: “It was quite the most incredible event that ever happened to me in my life. It was as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.” (Modern Physics, p. 154)

The huge deflections could only occur if the positive charge were concentrated in an incredibly small volume at the center of the atom: the atomic nucleus.

Visualize a small bowling ball plowing through jello (plum pudding) vs. a small bowling ball hitting another, larger, bowling ball (gold nucleus). Compare the odds of the smaller ball bouncing back from the jello with the odds of it bouncing back from a collision with the larger ball.

Rutherford proposed what is now known as the “planetary model” of the atom; that is, the electrons traveled in orbits around the tiny positive nucleus much like planets around the sun.
The electrons didn’t alter the path of the alpha particles at all; imagine marbles in the way of a small bowling ball.

This model, though it still serves us today for purposes of visualizing the atom, had a great weakness; it couldn’t be used to explain why atoms don’t collapse in on themselves.

It had been demonstrated (remember Maxwell’s equations?) that accelerating charges radiate energy. If the electrons “orbited” the nucleus (an accelerated motion), why didn’t they lose energy (emitting it at a frequency equal to that of their motion around the nucleus) and eventually spiral down into it? (Physics 3rd Ed., Tipler, p. 1157)

We’ll answer the question of atoms collapsing first, but before we can, we have to jump back in time from 1911 to 1900, and Max Planck.
1900- Max Karl Ernst Ludwig Planck (1858-1947) discovered that energy is quantized.

Investigating inconsistencies in the mathematical description (model) of the way certain objects emanate energy, Planck demonstrated that energy exists only at discrete pieces, that he called quanta (singular quantum, a Latin word meaning “how much?”). (Asimov’s Chronology of Science and Discovery, Asimov, p. 473)

In other words, when an object radiates energy, the energy can be visualized as existing in tiny packets or bundles. Planck’s discovery can be succinctly summarized as follows:

Energy (E) = Planck’s constant (h) x frequency of the radiation (n)
Planck at first didn’t realize the importance of his work, taking $h$ to be nothing more than a mathematical “fudge-factor” that allowed the numbers to work out as part of his mathematical model.

It wasn’t until five years later that Albert Einstein demonstrated the importance of quanta the significance as part of the natural world.

♦ Planck won the 1918 Nobel Prize in Physics for his work. (Asimov’s Chronology of Science and Discovery, Asimov, p. 474)

♦ Planck’s son was put to death for his part in the 1944 plot to assassinate Adolph Hitler.
At the age of 26 in 1905- Albert Einstein (1879-1955) revolutionized physics

- He demonstrated conclusively that atoms exist.

Although it may appear that the atomic theory of matter was universally accepted by the end of the nineteenth century, that was not the case. Certainly, most physicists believed in it, but there was still opposition. A principal leader in the anti-atomic movement was the renowned Austrian physicist Ernst Mach. Mach was an absolute positivist, believing in the reality of nothing but our own sensations. A simplified version of his line of reasoning would be that since we have never seen an atom, we cannot say anything about its reality. Also, the Nobel Prize-winning German physical chemist Wilhelm Ostwald supported Mach, contending that we should think of atoms only as hypothetical constructs, useful for bookkeeping in chemical reactions. (Modern Physics, pp. 14-15)
Einstein explained the so-called Brownian motion of tiny particles in a fluid in terms of the motion of molecules colliding with the particles (remember temperature as the measure of the vibration of atoms/molecules). Einstein was able to determine the approximate mass and sizes of atoms and molecules. (Modern Physics, pp. 15-16)

In 1908, Perrin presented data that agreed with Einstein’s predictions; he determined the size of an atom as about a hundred-millionth of a centimeter in diameter. (Asimov’s Chronology of Science and Discovery, Asimov, pp. 501-502)
He postulated the Special Theory of Relativity. It is relativity, because velocity has meaning only as relative to an observer, there being no such thing as “absolute rest” against which an “absolute motion” can be measured. There is also no such thing as “absolute space” or “absolute time,” since both depend on velocity and therefore have meaning only relative to the viewer. Nevertheless, despite this absence of absolutes, the laws of physics still held for all “frames of reference.” In particular, Maxwell’s equations still held, though, the much older and more revered laws of motion as worked out by Newton had to be modified. (Asimov’s Chronology of Science and Discovery, Asimov, pp. 489-490)

The theory is special, because it confines itself to the special case of objects that are moving at constant velocity. Under those conditions, the theory does not take into account the effect of gravitational interaction, which are everywhere present and which force accelerations on motion. (Asimov’s Chronology of Science and Discovery, Asimov, pp. 489-490)

It set the speed of light in a vacuum as the “ultimate speed limit”.
Light will travel slower than this in other media, and hence other objects will travel faster than light does in those media, but never faster than 186,289.5 mi/s (Cerenkov radiation is an example of this).

♦ It described the properties of objects moving close to speed of light in vacuum.

From the viewpoint of an observer at rest with respect to the object moving at nearly the speed of light in vacuum, it will appear that the object’s mass has increased, it’s length has contracted, and time has slowed down for it. These are purely relative phenomena; for instance, the mass hasn’t “really” increased, for in the frame of reference of the moving object, the mass is unchanged (and in fact, in the object’s reference frame, it isn’t “moving” at all- it is the observer “at rest” who is moving!).

…the much older and more revered laws of motion as worked out by Newton had to be modified. (Asimov’s Chronology of Science and Discovery, Asimov, pp. 489-490) In other words, Newton’s three Laws of Motion aren’t laws at all! Einstein’s theory is a much more general description of motion- when objects are moving at “everyday” speeds, the more complicated math reduces to Newton’s laws.
Energy \( (E) = \text{mass} \ (m) \times \text{the speed of light in vacuum} \ (c)^2 \), or \( E = mc^2 \)

Mass and energy can each be converted to the other in amounts dictated by this formula; since the speed of light is so large, the formula demonstrates that a small amount of mass represents an equivalent enormous amount of energy.

The laws of conservation of mass and conservation of energy were superseded by what is sometimes known as the Law of Conservation of Mass-Energy. Mass can disappear, but energy must appear in its place, and energy can disappear, but mass must appear in its place as dictated by Einstein’s formula.

The energy liberated in radioactive decay was soon linked to mass changes within the atom in accordance with Einstein’s equation; thus the Law of Conservation of Energy was not being violated. Because no one at this point understood the internal workings of the atom, scientists could only refer to this energy source as atomic energy.
He confirmed that Planck’s quantization of energy is a real property of nature, and not simply a mathematical construct.

He mathematically modeled the photoelectric effect - the situation in which metals emit electrons when light is shined upon them. Einstein proposed that light consisted of quanta (now called photons) that were absorbed by the electrons, causing them to be ejected.

This new view of light revealed its truly paradoxical nature; it behaves as both a particle and a wave, so in a sense, both Christiaan Huygens and Isaac Newton were right.

Einstein won the 1921 Nobel Prize for Physics for his description of the photoelectric effect (not for his Special Theory of Relativity). (Asimov’s Chronology of Science and Discovery, Asimov, p. 491)

The relationship between theoretical and experimental physicists is always an interesting one. The great theoretician Albert Einstein never did an experiment with his own hands (to the author’s knowledge, at least), while the great experimentalist Lord Rutherford was so poor in mathematics that the famous Rutherford formula for alpha-particle scattering was derived for him by a young mathematician, R. H. Fowler. (Thirty Years That Shook Physics, Gamow, p. 140)
1913- Niels (Neelz) Henrik David Bohr (1885-1962), a Danish physicist, solves the problem of the “collapsing atom”.

He postulated that the atom does not collapse in on itself because the electrons, though accelerating, are allowed to exist without radiating energy if they are in certain energy states, or “shells” around the nucleus (energy states in between are forbidden).

Note: “subshell” would be the correct term to use here, because electron energy depends on both the n and l quantum numbers, and electrons with identical values for n and l are said to be in the same “subshell”.

Bohr also proposed that if an electron moves from a higher energy state (shell) to a lower, it gives off a quantum (photon) with an energy dictated by Planck’s formula.

Energy (E) = E_{initial} - E_{final} = Planck’s constant (h) x frequency of the radiation (n)

Conversely, the electron can absorb a quantum and move from a lower to a higher energy state as described by this formula.

This one theory ties together Planck’s constant (h), Einstein’s photons, and Balmer’s spectral lines.
Each chemical element has certain allowed energy states for the electrons of its atoms. These energy states are unique to that element and do not change. (Physics 3rd Ed., Tipler, p. 2) Thus, each time the electrons change energy states (shells), a photon with the same value of $h\nu$ will result. Since the frequency ($\nu$) will be the same for each particular transition, so will the color. Thus, the color of light emitted by a particular element is unique to that element and is always the same. Bohr’s theory passed the ultimate test; with it he was able to correctly predict the hydrogen spectrum (the formula developed by Balmer was no longer empirical).

Note: “subshell” would be the correct term to use here, because electron energy depends on both the $n$ and $l$ quantum numbers, and electrons with identical values for $n$ and $l$ are said to be in the same “subshell”.

♦ Bohr was a student of Rutherford’s.
http://www.nzedge.com/heroes/rutherford.html

♦ Bohr was awarded the Nobel Prize for Physics in 1922. (Asimov’s Chronology of Science and Discovery, Asimov, p. 519)
1914- Rutherford established the concept of the proton.

In 1912 Thomson studied the manner in which positive rays were deflected by magnetic and electric fields. He balanced those fields in such a way that particles of different charge-to-mass ratio curved differently and fell in different spots on a photographic plate. (Asimov’s Chronology of Science and Discovery, Asimov, p. 516) Rutherford studied them and came to the conclusion, in 1914, that the positive rays involving hydrogen nuclei were the smallest of all and that no smaller positively charged particles existed. He therefore called the hydrogen nucleus a proton (form the Greek word for “first”). (Asimov’s Chronology of Science and Discovery, Asimov, p. 524)
Of course it didn’t make too much sense that the atomic nucleus should consist of protons. After all, the protons, being positively charged, would repel each other. The natural suggestion, then, was that electrons were also present in the nucleus and that their negative charges acted as a kind of cement. This seemed all the more logical since radioactive changes caused atoms to eject electrons in the form of beta particles, and these seemed to come from the nucleus.

It seemed, then, that all atoms were made up of equal numbers of proton and electrons, with some of the electrons inside the nucleus and some circling around it.

For example, a helium atom was known to have a mass four times that of a proton, but a nucleus with a charge only twice that of a proton. It was thought that there were four protons and two electrons in the nucleus (mass 4, charge +2), and two electrons orbiting the nucleus (mass 0, charge -2). (Asimov’s *Chronology of Science and Discovery*, Asimov, p. 524)
1932- James Chadwick (1891-1974) discovered the neutron

- By 1925, it had been proven that that notion of a nucleus composed of protons and electrons was incorrect. ([Asimov’s Chronology of Science and Discovery](Asimov’s Chronology of Science and Discovery, Asimov, pp. 582-583))

- In 1925, when Uhlenbeck and Goudsmit worked out the concept of particle spin, it had become clear that something was wrong with the proton-electron notion of nuclear structure. Protons and electrons both had a spin of either $+\frac{1}{2}$ or $-\frac{1}{2}$. If twenty-one such spins, or in fact any odd number of such spins, were added up, the total spin should be one of the half-integers: $\frac{1}{2}$, or $1\frac{1}{2}$, or $2\frac{1}{2}$, and so on. The actual measured spin of the nitrogen nucleus, however, was an integer. The nucleus, therefore, could not contain an odd number of particles but had to contain an even number. There were other nuclei that shared this anomalous characteristic. ([Asimov’s Chronology of Science and Discovery](Asimov’s Chronology of Science and Discovery, Asimov, pp. 582-583))
Chadwick was studying particles without charge, and examined their interactions with paraffin (a wax containing hydrocarbons obtained from the distillation of petroleum). He noticed that the neutral particles knocked protons out of the atomic nuclei in paraffin, and proposed that the particle had a mass equivalent to that of protons. (Asimov’s Chronology of Science and Discovery, Asimov, pp. 582-583)

He named the particles neutrons; a concept first postulated by Rutherford.

As soon as the neutron was discovered by Chadwick, Werner Karl Heisenberg (1901-1976) pointed out that atomic nucleus must be made up of protons and neutrons rather than protons and electrons.

Thus a helium atom has two protons and two neutrons in the nucleus (mass 4, charge +2), and two electrons orbiting the nucleus (mass 0, charge -2).

However, the question remained unanswered: with only positively charged protons in the nucleus, how does it avoid exploding apart?

Chadwick was a student of Rutherford’s. He was awarded the Nobel Prize for physics in 1935 for his discovery. (Asimov’s Chronology of Science and Discovery, Asimov, pp. 582-583)
(1796 – 1832) Nicolas Léonard Sadi Carnot

- Second Law of Thermodynamics
- Carnot Heat Engine

Carnot Heat Engine

\[ \text{Performance of System} = \frac{\text{Energy Sought}}{\text{Energy that Costs}} \]

HIGH – TEMPERATURE RESERVOIR \( T_h \)

HEAT ENGINE

\( Q_h \)

\( Q_l \)

LOW – TEMPERATURE RESERVOIR \( T_l \)

HEAT PUMP/REFRIGERATOR

\( Q_h \)

\( Q_l \)

Conservation of Energy

\[ W = Q_h - Q_l \]
Carnot Efficiency

\[
\text{Temperature}_{\text{hot}} - \text{Temperature}_{\text{cold}} / \text{Temperature}_{\text{hot}}
\]

Seabrook Nuclear Power Generation Station operates at a thermal power of...
Nuclear Power Plant