



Polywell: Isotopes & Radiation

The Polywell
Reactor

Nuclear
Reactions

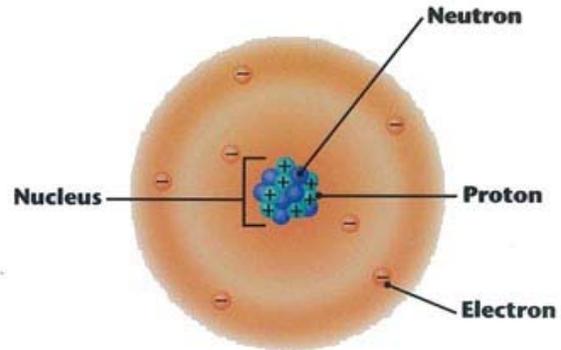
Alternatives
Inappropriate

Hidden Costs
of Carbon

Web Site
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Isotopes & Radiation

Solids, liquids, and gases are all made out of **Atoms**. Atoms are made out of organized and coherent clusters of **Electrons**, **Neutrons**, and **Protons**. The protons and neutrons are concentrated in the center of each atom; collectively this single concentration is called a **Nucleus**. (The plural of nucleus is **Nuclei**.) Both protons and neutrons are also called **Nucleons**. Nucleons are held together with the strongest and shortest-range force, which is called (amazingly!) the **Nuclear Force**. The most common **Hydrogen atoms** (H1) have a nucleus of one proton and zero (0) neutrons. However, a few hydrogen atoms can also have one or two neutrons, in addition to the single proton. The uncommon hydrogen with one proton and one neutron is also called **Deuterium** (H2); the one with a proton and two neutrons is also called **Tritium** (H3). Atoms with an uncommon number of neutrons are called **Isotopes**. Atoms with 2 protons and 2 neutrons are called **Helium** (He4); atoms with 5 protons and 6 neutrons are called **Boron** (B11) and so on. (The symbol and name for each element are shown in red in the table below.) The number of protons is called the **Atomic number**, which determines the name of an atom. (The atomic number, that is the proton number, for each element is printed in black *beneath* the red symbol for that element, in the table below.) The number of nucleons determines the **Mass number**. (The mass numbers for each element are given in black *above* the red symbol for that element, in the table below. Each isotope of an given element has a different mass number.)



1,2 H 1 Hydrogen																	3, 4 He 2 Helium						
6, 7 Li 3 Lithium	9 Be 4 Beryllium																	10, 11 B 5 Boron	12, 13 C 6 Carbon	14, 15 N 7 Nitrogen	16, 17, 18 O 8 Oxygen	19 F 9 Fluorine	20, 21, 22 Ne 10 Neon
23 Na 11 Sodium	24, 25, 26 Mg 12 Magnesium																	27 Al 13 Aluminum	28, 29, 30 Si 14 Silicon	31 P 15 Phosphorus	32, 33, 34, 36 S 16 Sulfur	35, 37 Cl 17 Chlorine	36, 38, 40 Ar 18 Argon
39, 41 K 19 Potassium	40, 42, 43, 44, 46, 48 Ca 20 Calcium	45 Sc 21 Scandium	46, 47, 48, 49, 50 Ti 22 Titanium	51 V 23 Vanadium	50, 52, 53, 54 Cr 24 Chromium	55 Mn 25 Manganese	54, 56, 57, 58 Fe 26 Iron	59 Co 27 Cobalt	58, 60, 61, 62, 64 Ni 28 Nickel	63, 65 Cu 29 Copper	64, 66, 67, 68, 70 Zn 30 Zinc	69, 71 Ga 31 Gallium	70, 72, 73, 74, 76 Ge 32 Germanium	75 As 33 Arsenic	74, 76, 77, 78, 80, 82 Se 34 Selenium	79, 81 Br 35 Bromine	78, 80, 82, 83, 84, 86 Kr 36 Krypton						
85 Rb 37 Rubidium	84, 86, 87, 88 Sr 38 Strontium	89 Y 39 Yttrium	90, 91, 92, 94, 96 Zr 40 Zirconium	93 Nb 41 Niobium	92, 94-100 Mo 42 Molybdenum	none Tc 43 Technetium	96, 104, 98-103 Ru 44 Ruthenium	104 Rh 45 Rhodium	102, 108, 110, 104-106 Pd 46 Palladium	107, 109 Ag 47 Silver	106, 108, 114, 110-112, 116 Cd 48 Cadmium	113 In 49 Indium	112, 114, 120, 122, 124 Sn 50 Tin	121 Sb 51 Antimony	120, 122, 128, 124-126, 130 Te 52 Tellurium	127 I 53 Iodine	124, 126, 134, 128-132, 136 Xe 54 Xenon						
133 Cs 55 Cesium	130, 132, 134-138 Ba 56 Barium		174, 176-180 Hf 72 Hafnium	180, 181 Ta 73 Tantalum	180, 182, 183, 184, 186 W 74 Tungsten	185 Re 75 Rhenium	184, 192, 186-190 Os 76 Osmium	191, 193 Ir 77 Iridium	192, 198, 194-196 Pt 78 Platinum	197 Au 79 Gold	196, 204, 198-202 Hg 80 Mercury	203, 205 Tl 81 Thallium	204, 206-208 Pb 82 Lead	209 Bi 83 Bismuth	none Po 84 Polonium	none At 85 Astatine	none Rn 86 Radon						
none Fr 87 Francium	none Ra 88 Radium	139 La 57 Lanthanum	136, 138, 140 Ce 58 Cerium	141 Pr 59 Praseodymium	142, 143, 145, 146, 148, 150 Nd 60 Neodymium	none Pm 61 Promethium	144, 152, 154, 148, 149, 150 Sm 62 Samarium	151, 153 Eu 63 Europium	152, 160, 154-158 Gd 64 Gadolinium	159 Tb 65 Terbium	156, 158, 160-164 Dy 66 Dysprosium	165 Ho 67 Holmium	162, 164, 166, 167, 168, 170 Er 68 Erbium	169 Tm 69 Thulium	168, 176, 170-174 Yb 70 Ytterbium	175 Lu 71 Lutetium							
none Ac 89 Actinium	none Th 90 Thorium	none Pa 91 Protactinium	none U 92 Uranium	none Np 93 Neptunium	none Pu 94 Plutonium	none Am 95 Americium	none Cm 96 Curium	none Bk 97 Berkelium	none Cf 98 Californium	none Es 99 Einsteinium	none Fm 100 Fermium	none Md 101 Mendelevium	none No 102 Nobelium	none Lr 103 Lawrencium									

6, 7 — Mass Numbers of Stable Isotopes
 Element Symbol — **Li**
 3 — Atomic Number
 Element Name — Lithium

The mass numbers given in the table are the known **stable isotopes**, which do not break down spontaneously. **Unstable isotopes** are not shown because there are too many of them. When unstable isotopes break down into new isotopes, they usually emit alpha, beta, or gamma radiation. It says "none" above Uranium (and many other elements) because *all* of the isotopes of Uranium are unstable and radioactive. In print, isotopes are often shown like this: U235 or B11. The number that follows the symbol for the element is the mass number of the isotope. A *nuclear* reaction might be indicated in this manner: H1 + B11 --> 3 He4

An H1 isotope is the same as a proton; and a He4 isotope is the same as an alpha. The "3" coefficient in front of the He4 means there are 3 He4 nuclei. Notice that the isotopes present *before* the reaction are *different* from the isotopes *after* the reaction. The mass number matters a lot: for example, the above reaction would not happen if we used B10 instead of B11.

Radioactivity: α , β , γ (alpha, beta, gamma)

In 1896 the French physicist Henri Becquerel was investigating x-ray phosphorescence. He wanted to see if the sun would make potassium-uranyl sulfate crystals emit x-rays. (He had already discovered that a CRT face would emit x-rays when the electron beam was hitting it. And he knew that x-rays shining on the outside of a package wrapped tightly in black paper would expose the film inside.) In anticipation of a sunny day, he left a sheet of fresh, tightly wrapped film in his desk with a piece of the potassium-uranyl sulfate crystal sitting on top of the package. But the sun didn't come out for several days. And because he was afraid the film wasn't fresh any more, he developed it without letting the sun shine on the crystals. He expected the images to be very feeble, but on the contrary, silhouettes of the crystals appeared with great intensity.

Becquerel found that all *compounds* of uranium and *pure* uranium behaved the same way. They all emitted what seemed to be x-rays, yet they did not need to be excited first with light or an electron beam. The uranium and its compounds could ionize gases, which permitted the gases to conduct an electric current. Yet this **radiation** seemed to be constant over time, varying only in proportion to the amount of uranium present.

In 1898 physicists Marie Sklodowska-Curie of Poland and Pierre Curie of France conducted a systematic study to determine which other elements and compounds emitted this mysterious radiation. They found that the element thorium behaved much like uranium. But the radiation from pitchblende, a uranium ore, was far greater than it should have been, considering the known percentage of its uranium content. They therefore suspected that the pitchblende contained some other previously undiscovered element. Beginning with a large sample of pitchblende, they employed a series of chemical separation techniques, always discarding the separated fraction, which did not emit the disproportionately high radiation. Eventually, they isolated a new radioactive element, which they called polonium in honor of Marie's home country.

Four years later, starting with 100 kg of pitchblende, and using similar techniques, they were able to isolate 0.1 g of an even more intensely radioactive substance, which they called radium. After Pierre's accidental traffic death in 1906, Marie was appointed in his place as a professor of physics at the Sorbonne in Paris. She was awarded the Nobel Prize in 1911 for her discovery of polonium and radium. She died in 1934 of leukemia, which was probably caused by overexposure to the radiation involved in her research.

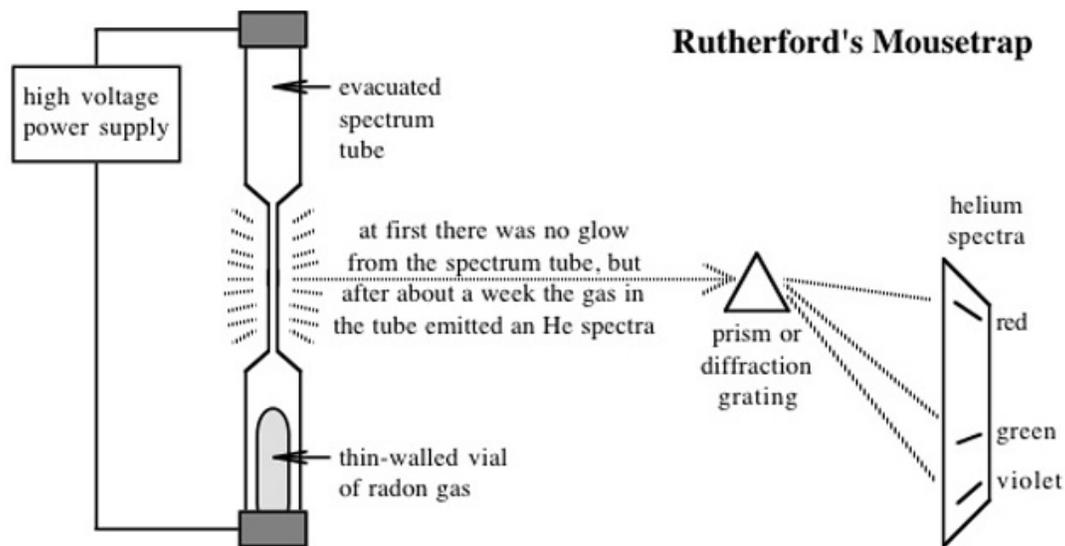
Meanwhile, Ernest Rutherford was measuring the "penetrating power" of uranium's mysterious radiation. He discovered that the radiation was made up of three different types of "rays" with very different powers of penetration.

The intensity of what he called **alpha α** rays, could be reduced to one-half as much by a very thin (0.005 mm) piece of aluminum foil. A similarly thin piece would cut the intensity by half again as much, to a total intensity of one-fourth; and a third piece would cut the total to one-eighth, etc.

Beta β ray intensity could be reduced to one-half as much by a 0.5 mm aluminum sheet; and again each additional 0.5 mm sheet would cut the prevailing amount by one-half. In general, the thickness of a specific material required to reduce a certain type of radiation by one-half is called a **half-thickness**.

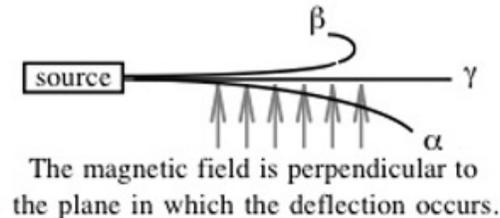
The half-thickness for **gamma γ** the third type of uranium radiation was found to be 80 mm of aluminum.

Rutherford sealed a thin-walled vial of alpha-emitting radon gas inside a second glass tube. All the air was pumped out of the second outer tube before sealing. Rutherford attempted to ionize any possible remaining gas in the outer tube, and at first he was unsuccessful. But as time passed, gas accumulated in the second outer tube.



When the gas was ionized and its spectral lines were examined, it was found to be helium. Rutherford therefore proposed that alpha particles were helium nuclei.

A variety of people conducting experiments at about the same time found that the alphas were deflected in one direction by a magnetic field, in the same way as positive charges; but the beta rays were deflected in the opposite direction, in the same way as electrons. The gamma rays were not deflected by a magnetic field, possibly because they were not charged.



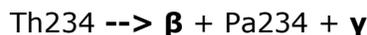
By measuring the radius of deflection in the magnetic field, it was determined that the alphas were much more massive than the betas. The betas had about the same mass and charge as electrons.

The emission of alpha and beta particles raised interesting questions about the conservation of charge and mass in chemical reactions. But Pierre Curie had found that a gram of radium produced about 100 calories of heat per hour, day in and day out, year after year. This was far more heat than chemists had come to expect from normal chemical reactions. So questions arose about the conservation of energy as well.

Perhaps something more than ordinary chemical change was involved. Rutherford and Frederick Soddy proposed that atoms were *not* conserved in radioactive emissions. They suggested that when an atomic nucleus emits a certain type of particle, it *loses* that amount of mass and charge. For example, when a uranium nucleus emits an alpha particle, it *loses* four atomic mass units (amus) of mass, and two units (elementary charges) of charge. But nuclear charge is the same as atomic number (or proton number), and that is what determines the name of an element. So when uranium loses two units of charge, its *atomic number decreases* from 92 to 90, and its *name changes* from uranium to thorium! Also, if we suppose that the original uranium nucleus had a mass number of 238, then the new thorium produced by the alpha emission would have a

mass of 234. We show such a reaction this way: $U_{238} = He_4 + Th_{234} + \gamma$. Notice that mass number is conserved, even though the atoms are not. We show the alpha as an He_4 and we show the gamma as part of the reaction, even though it has no charge or mass.

Since such reactions involve the disintegration of a **parent** element to form radiation and a new **daughter** element; they came to be called **nuclear decay** reactions. Since total mass and charge are conserved in a nuclear decay reaction, interesting things happen during a beta (electron) decay, such as the decay of Th_{234} .



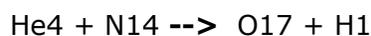
Notice first that since the charge of the beta is -1, the atomic number of the daughter *increases*. (From the table, we see that the atomic number of Th is 90, and the atomic number of Pa is 91.) Also notice that since the mass of an electron –a beta– is essentially zero when compared to a proton or a neutron, we round it off to "0," and there is no change in the mass number of the daughter. As before, mass number and charge are shown to be conserved, even though the atoms are not. As before, a gamma is emitted also.

A gamma is a high-energy photon, so the energy state of a nucleus must decrease when a high-energy gamma is emitted. The change in energy state of an atom's nucleus is a probability problem. We have difficulty predicting exactly when the energy state of a nucleus is going to change. Although we can experimentally determine the time it takes for half of a large population of radioactive nuclei to decay, it is impossible to say when decay will happen to one particular nucleus in that population.

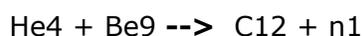
If it takes 24.1 days for half of the atoms in a 5.04 g sample of Th_{234} to decay, then we say that the **half-life** of Th_{234} is 24.1 days. In another 24.1 days, half of the remaining 2.52 g will decay, leaving 1.26 g, and in yet another 24.1 days 0.63 g of Th_{234} will remain. So it takes a total of 72.3 days for 5.04 grams of Th_{234} to decay to 0.63 grams.

Within an atom's nucleus, the electrical repulsion of like-charged protons is evidently overwhelmed by some type of highly attractive force. And since one atom's nucleus does not seem to be attracted to another's, it was thought that nuclear forces must be very strong and very limited in range. But if the nuclear force was so strong, how could atoms decay? In 1928 while studying in Germany, the Soviet physicist George Gamow developed an explanation for the escape of alpha particles from the nucleus. When he attempted to write the wave-mechanical equation for an alpha particle he found that its probability limits extended quite far beyond the short estimated range of the nuclear force. Thus, whenever an alpha's wave function collapsed outside the limited range of the nuclear force, the mutual repulsion of the positive alpha particle and the positive nucleus accelerated them away from each other.

Alpha, beta, and gamma emission is produced by natural radioactive decay. But Rutherford found that if he bombarded non-radioactive elements with such radiation, some very interesting synthetic emissions were produced. For example, he found that when nitrogen gas was bombarded with alpha particles, proton (hydrogen) emissions occasionally resulted. Upon further investigation it was established that oxygen atoms were being produced at the same time:



Similarly, James Chadwick was able to show that **neutron n1** emissions could be produced when beryllium was bombarded with alpha particles:



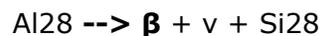
Once Chadwick had established the existence of *neutrons*, it was easy to account for the relation between atomic number and mass number. The atomic number was the *proton* number, and the mass number was the *nucleon* number. Also, neutrons made it possible to explain how the mass number of an element could vary. The number of *protons* determined the atomic number, the chemical properties, and the name of an element. But, because different atoms of the same element could have different numbers of *neutrons*, it was possible for them to have different mass numbers. Thus, isotopes of the same element all have the same proton number, but their neutron number can vary.

With all the artificial **transmutation** of one element into another by alpha bombardment, it was only a matter of time before someone tried to use other particles. And it was only a matter of time before someone tried to fulfill the ancient dream of the alchemists. Gold can be produced by slamming isotopes of hydrogen nuclei called deuterium into platinum:

$$H_2 + Pt_{196} \rightarrow Au_{197} + n_1$$

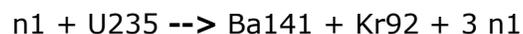
The catch is that gold produced in this manner is much more expensive than gold mined from the earth. But the equation is still interesting because it's another example of a reaction that produces neutrons. Such reactions turn out to be significant because neutrons are particularly useful as nuclear bullets. They are not deflected by electron orbitals or a nuclear charge the way that charged particles are, so they are much more likely to find a nuclear target.

Al²⁸ is an example of an unstable isotope that can be produced by *neutron* bombardment of ordinary stable aluminum: $n_1 + Al_{27} \rightarrow Al_{28}$. The Al²⁸ produced in this reaction quickly decays into a normal beta, a neutrino ν , and silicon, which has an atomic number of one more than aluminum:



Enrico Fermi, an Italian physicist was particularly interested in that reaction because it implied to him the possibility of going beyond the 92 elements found in nature. (In 1934 it was generally believed that there were no elements in the periodic table beyond uranium.) He believed that the bombardment of U²³⁸ with neutrons should likewise produce an unstable isotope of uranium that would quickly decay into a substance with atomic number 93. It would be the first synthetic element.

But when he tried it, the results seemed at first to be quite confusing and they were definitely not what he had expected. Instead of a new element with atomic number 93, there seemed to be small amounts of different isotopes with small atomic numbers such as 36, 38, 39, 54, 56, and 57. Because the quantities were so small and the results so hard to accept it was nearly five years before two Austrian physicists, Lise Meitner and Otto Frisch were finally able to make the conceptual leap. They proposed that while trying to make the first synthetic element, Fermi had instead *split the atom*. Additional research soon established that neutrons were another product of this **fission**. One of the reactions resulting from Fermi's fission was:



Which of course is what made the chain reaction possible: this one reaction has changed human civilization profoundly.

Effects of Radiation on Health

Alpha, beta, gamma or neutron radiation can be released by nuclear reactions or decay. All four types can cause ionization of atoms, usually by knocking an electron loose from an

atom, and giving the rest of the atom a net positive electrical charge. Neutrons can cause already existing chemicals in air, water or other nearby materials to become unstable and radioactive. As these unstable forms of natural materials return to their normal stable state, they also can release ionizing radiation. Ionizing radiation can damage living cells: in particular it can alter reproductive material such as DNA, making it permanently defective. DNA contains the directions for making new cells. When it becomes defective, the new cells and their new DNA will be defective, and the damage will be passed from one generation to the next, indefinitely.

Gamma radiation is an electromagnetic wave that easily passes through the body, like light passing through a window. No radiation remains in the body after exposure to gamma radiation. However, the ionizing damage it may have caused on the way through remains.

Beta radiation is made of high energy electrons, which can penetrate skin but cannot penetrate through the whole body like gamma radiation. Beta particles outside the body can cause serious burns and other skin anomalies, including skin cancer.

Alpha particles are helium nuclei, which can be stopped by human skin, but they may damage it in the process. Both alpha and beta particles can penetrate cell membranes more easily than they penetrate skin. Thus ingesting, inhaling or absorbing radioactive material capable of emitting alpha or beta particles (thereby placing them inside delicate body parts such as the lungs, heart, brain or kidneys) always poses serious threats to human health. For example, plutonium is an alpha emitter, and no quantity inhaled has been found to be too small to induce lung cancer in animals.

Neutrons escaping from some nuclear reactions can penetrate the human body. They are among the most biologically destructive of the fission products. They have a short range, however, and in the absence of fissionable material they will quickly be absorbed by non-radioactive materials. Gamma rays and neutrons are able to inflict harm on humans even when the radioactive material emitting them is outside the body.

Ionizing radiations emitted from within the body by radioactive chemicals taken in by inhalation, ingestion or absorption, are even more damaging because they are so close to delicate cell structures. The body is not able to distinguish between radioactive and non-radioactive chemicals and will as readily incorporate the one as the other into tissue, bone, muscle or organs, identifying them as ordinary nutrients. The radioactive chemicals remain in the body until biologically eliminated in urine or feces, or until they decay into other chemical forms, which may or may not be radioactive. Radiochemical analysis of urine or feces is the preferred test for most types of internal contamination with alpha or beta particles.

Here is a summary of the effects of different doses of radiation on the human body after acute, whole-body exposure: **rad** - radiation absorbed dose - is the amount of ionizing radiation that bombards a body.

Less than 5 rad: No immediate observable effects.

5 to 50 rad: Slight blood changes detected by medical testing.

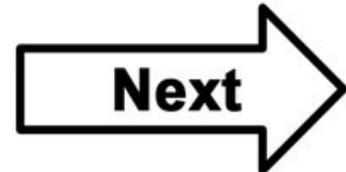
50 to 150 rad: Temporary drop in production of new blood cells; nausea, fatigue and vomiting for one or two days. Spontaneous abortion if pregnant.

150 to 250 rad: Nausea and vomiting on the first day. Diarrhea and probable skin burns. Apparent improvement after about two weeks and thereafter. May develop cancer. Will probably have a shortened lifespan. Genetic effects.

250 to 600 rad: Severe blood changes and other symptoms appear immediately. Up to one-half of those exposed will die within 30 days without intensive medical attention. Blood forming organs have been damaged or destroyed: without white blood cells, infection is likely. Isolation, antibiotics, and transfusions may provide the bone marrow with time to generate new blood cells, and full recovery is possible. At the upper end of the dose range, a bone marrow transplant may be required to produce new blood cells.

600 to 1000 rad: Weakness, nausea, vomiting and diarrhea followed by apparent improvement. Often death occurs in 3 to 10 days. The gastrointestinal system has been destroyed and nothing can be done. Medical care is for comfort only.

More than 1000 rad: Central nervous system damage stops control of body functions, including breathing and blood circulation. Death occurs within days or hours. Nothing can be done. Medical care is for comfort only.



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