## 4.6 NUCLEAR ENERGY

One kilogram of uranium 235 contains about as much energy as 3000 metric tons of coal or 14,000 barrels of petroleum. Nuclear power does not emit carbon dioxide, a known greenhouse gas. The expected decrease in lifetime due to exposure to the processes involved in operating a nuclear power plant is around 30 minutes compared to 3.6 years for being overweight and seven years for a one pack a day smoker. The number of accidental deaths per Gigawatt-year of energy production is four deaths for coal mining, 2.6 for surface mining of coal, 0.4 for oil drilling and 0.2 deaths for uranium oxide mining. For these reasons, many countries, France and Japan in particular, have opted for nuclear power over fossil fuels for electricity generation. In the following we consider the processes involved in making nuclear power. A deeper assessment of the risks involve will be found in Chapter Eight.

### 4.6.1 NUCLEAR PHYSICS

Atomic nuclei are specified by two numbers, the atomic number, $Z$, which gives the number of protons and therefore determines the element, and the neutron number, $N$. The sum of these two numbers, the total number of nucleons, is the mass number, $A$. Different isotopes of an element have the same atomic number but different numbers of neutrons and therefore different mass numbers. So for example ${}^{12}_{6}C$ and ${}^{14}_{6}C$ have the same chemical properties since they have the same number of protons (and therefore the same number of electrons which give the element its chemical properties) but different numbers of neutrons. Electrons are designated as $e^-$ and neutrons as ${}^{1}_{0}n$ in the following. Nuclear reactions also involve positively charged electrons, $e^+$ called positrons which have very short lifetimes. The neutrino, $\nu$ and anti neutrino, $\bar{\nu}$ are also created in nuclear reactions. Neutrinos are nearly massless particles which do not interact very strongly with normal matter, making them very difficult to detect.

Although the protons found in the nucleus are positively charged and repel each other, they are held together by the strong nuclear force. Neutrons in the nucleus also interact with each other and the protons via the strong force but do not have charge. The nucleus of different isotopes, then, can be expected to be more or less stable depending on the number of neutrons since a larger number of neutrons increases the relative amount of nuclear force without increasing the repulsive electric force. This is particularly true for heavier elements; the ratio of neutrons to protons for isotopes which are stable increases with the atomic number. The nuclear binding energy per nucleon is defined to be the energy needed to separate the protons and neutrons in a nucleus from each other divided by the number of nucleons present. A plot of binding energy per nucleon versus the number of mass number is shown in Figure 4.15. As can be seen, iron has the highest bonding energy per nucleon and thus has the most stable nucleus of any element. The fact that all elements heavier than iron have lower binding energies means there is at least the potential for these elements to lose nucleons and become more stable. This is the basis behind radioactive fission.

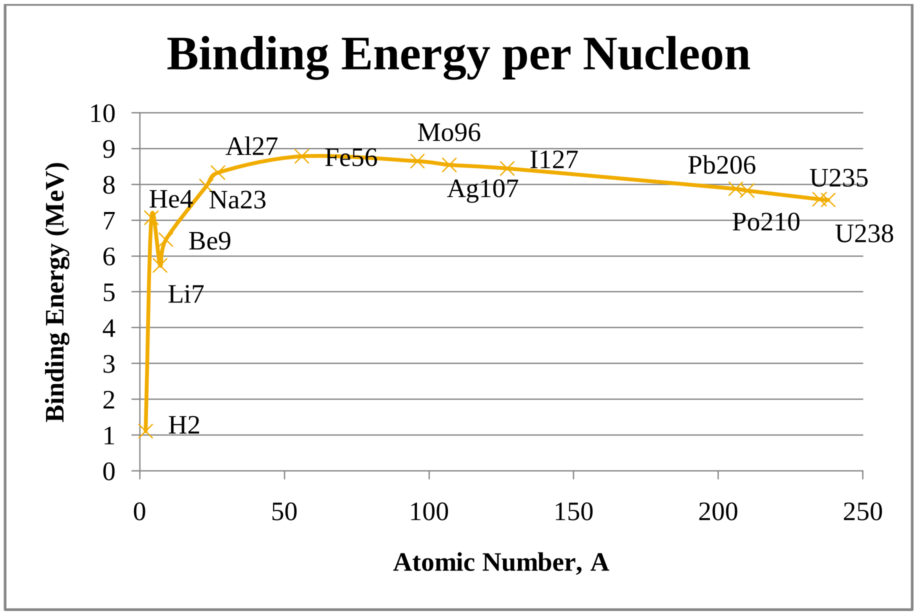


Figure 4.15 Binding energy per nucleon for select isotopes.

The nuclei of certain isotopes of some heavy elements undergo spontaneous decay to form new, lighter elements. The fragments from the decay have less total mass compared to the original nuclei; the missing mass is converted to energy according to the famous equation, $E = mc^2$ where $c = 2.999 \times 10^8\ m/s$ is the speed of light. From this equation it is clear that only a small amount of mass is needed to provide large amounts of energy. There are four major types of decay processes. Table 4.6 shows an example of each type of decay.

| Process | Example | Approximate Energy Released |
|---|---|---|
| **Alpha Decay** | ${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He$ | $4MeV$ |
| **Beta Decay** | ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + e^- + \bar{\nu}$<br>${}^{12}_{7}N \rightarrow {}^{12}_{6}C + e^+ + \nu$ | $9MeV$ |
| **Gamma Decay** | ${}^{A}_{Z}X^* \rightarrow {}^{A}_{Z}X + \gamma$ | $4MeV$ |
| **Fission** | ${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3{}^{1}_{0}n$<br>${}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2{}^{1}_{0}n$ | $200MeV$ |

Table 4.6 The four types of radioactive decay processes. $1eV = 1.602 \times 10^{-19}J$.

In alpha decay the nucleus emits a helium nucleus which has two protons and two neutrons. Gamma decay can occur for an arbitrary element, $X$, in an excited energy state (designated by the asterisk). The emitted product is a high energy electromagnetic photon, called a gamma photon, with a frequency above $10^{20}Hz$. Beta decay emits an electron and a neutrino; the neutrino emission is required for momentum conservation. Radioactive carbon dating is based on beta decay. Fission is the splitting of a nucleus into roughly equal parts. Two possible results of the fission of uranium 235 are shown in Table 4.6; there are hundreds of other possible decay products.

In Table 4.6 we see that fission typically produces more energy than the other decays and that a uranium nucleus can fission into a variety of so called daughter products. All four of the processes may occur spontaneously but the fission examples shown are triggered by a collision with a neutron which is the reaction occurring in most uranium fission reactors. In each of the four cases the total mass of the products is less than the mass of the original nucleus and the missing mass turns up as kinetic energy of the products according to $E = mc^2$. A more detailed discussion of radioactive decay can be found in [20].

Exactly when an individual nucleus will spontaneously decay is not predictable by the laws of physics. However, if there are a large number of identical nuclei they will collectively obey an exponential decay law according to the formula

$$R = \lambda N_0 e^{-\lambda t} \tag{4.8}$$

where $R$ is the activity, measured in Becquerel ($Bq$); $1Bq = 1\, emission/s$. Here $N_0$ is the orginal number of radioactive atoms and the original activity is $R_0 = \lambda N_0$. Rather than using the decay constant, $\lambda$, the time needed for half the material to decay, called the half life, is sometimes useful:

$$t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}. \tag{4.9}$$

Half lives of various decay processes can vary from fractions of a second to millions of years.

As mentioned above, the two isotopes of carbon are chemically identical but ${}^{14}_{6}C$ undergoes beta decay with a half life of $t_{1/2} = 5730yrs$. This isotope is created at more or less a constant rate in the upper atmosphere from nitrogen being struck by cosmic rays from space. From measurements made of the atmosphere there is a constant ratio of ${}^{14}_{6}C$ to ${}^{12}_{6}C$ in $CO_2$ of approximately $1.3 \times 10^{-12}$. This will also be the ratio of ${}^{14}_{6}C$ to ${}^{12}_{6}C$ found in living organisms since all organisms continue to take in $CO_2$ as they respire. Once an organism dies, however, the ${}^{14}_{6}C$ begins to decay and the ratio changes. Since this occurs at a known rate, the approximate date of death can be determined by comparing the ratio of carbon isotopes in the dead organism to the atmospheric constant rate of $1.3 \times 10^{-12}$.

### EXAMPLE 4.2 RADIOACTIVE CARBON DATING

Suppose a reed basket is found in an ancient burial site and the ${}^{14}_{6}C$ activity is measured to be 6.5 $Bq$ in a $100g$ sample. About how long ago was the basket buried?

Using equation (4.9) the decay constant is $\lambda = \frac{0.693}{t_{1/2}} = 3.84 \times 10^{-12}/s$. When alive the sample had $100g \times 1.3 \times 10^{-12} = 1.3 \times 10^{-10}g$ of ${}^{14}_{6}C$. A mole of ${}^{14}_{6}C$ weighs $14g$ so the original number of ${}^{14}_{6}C$ molecules is $N_0 = 1.3 \times 10^{-10}g \times 6.02 \times 10^{23} atoms/14g = 7.8 \times 10^{13} atoms$. Using equation (4.8) we have $6.5\, Bq = 7.8 \times 10^{13} \times 3.84 \times$

$10^{-12}/s\ e^{-(3.84\times10^{-12}/s)\ t}$. Solving for $t$ gives $t = 10.0 \times 10^{11} s = 31630\ years$ so the reed used to make the basket died about 32,000 years ago.

## 4.6.2 NUCLEAR REACTORS

If each of the neutrons emitted from a fission reaction strikes another uranium 235 nucleus it will stimulate another decay. So, taking the first fission reaction in Table 4.6 as typical, after one reaction $200MeV$ of energy is released and the three emitted neutrons hit three nuclei releasing $600MeV$ more in energy along with nine new neutrons. If there is enough uranium 235 present (a *critical mass*) so that each new neutron given off finds a nucleus to collide with (and the neutrons have the right energy), the amount of energy given off at each stage grows as $3^n$ where $n$ is the number of decays. This process is called a *chain reaction*. A reaction where the number of neutrons remains the same at each stage is said to be *critical*. A chain reaction where the number of neutrons continues to increase at each step is said to be *supercritical* and, if allowed to continue indefinitely, becomes an atomic explosion. If fewer neutrons occur at each stage the reaction is *subcritical* and the reaction eventually dies out. Notice that for a series of decays to become a chain reaction (sub, super or critical) there must be a critical mass of ${}^{235}_{92}U$ present; other isotopes of uranium will not support a chain reaction.

The above three types of chain reactions are complicated by the fact that the emitted neutrons are generally traveling too fast to be effective in stimulating further emissions. To maintain a chain reaction the neutrons usually must be slowed down using a *moderator*. These slower neutrons are called thermal neutrons. In nuclear reactors the concentration and arrangement of uranium 235 is carefully designed so that the chain reaction cannot continue to be supercritical past a given point. Because the concentration of fissionable uranium is relatively low, most reactors also required a surrounding material called a *reflector* which returns some of the neutrons to the uranium fuel in order to maintain the chain reaction at the critical level. Most reactor designs also include *control rods* which are made from substances that absorb neutrons so that the available neutrons with the right speed to stimulate decay can be controlled.

The most common type of nuclear reactor is the pressurize light water reactor (PWR). In this reactor the energy emitted by the radioactive fission of uranium is captured as thermal energy by water under high pressure (>150 atmospheres) and used to drive a steam turbine. The water acts as both moderator, to slow the emitted neutrons down to the right speed for further decay, and heat transfer medium. The fuel is in the form of uranium pellets, about the size of a dime with a concentration of ${}^{235}_{92}U$ of about 4%. These pellets are arranged in a fuel rod about one centimeter in diameter and three to four meters in length. The fuel rods are arranged in assemblies of around 250 rods and a reactor core has around 200 fuel rod assemblies. Control rods made of a material that absorb neutrons such as silver-indium-cadmium alloys are interspersed between the fuel rods; these can be raised or lowered into the core to control the rate of decay. Details of other reactor designs can be found in [21].

New reactor designs, termed Generation IV reactors, are designed to be smaller with lower fuel concentrations and fewer moving parts. They are planned to be inherently safe meaning that they will automatically shut down under their own power using natural convection in the event of operator error or failure of external electric power. One such design is the gas cooled pebble bed reactor. In this reactor the fuel is in the form of thousands of billiard ball sized spheres made of a carbon ceramic compound which encase mustard seed sized grains of uranium or other fissionable material. The reactor can be fueled while in operation by adding the fuel balls at the top and removing spend fuel balls from the bottom. Since the balls are already coated with a tough, high temperature resistant impermeable shell they can be disposed of without further processing. It is also impractical to use fuel in this form in a nuclear weapon. Helium is used as the heat transfer medium which means that the risk of steam explosion is eliminated and the reactor can operate at higher temperatures, making the thermal efficiency higher. Several experimental reactors with this design are now operating or are under development around the world.

Naturally occurring uranium is only around 0.7% ${}^{235}_{92}U$ with the remaining ore consisting of the ${}^{238}_{92}U$ isotope, which is more stable and does not undergo spontaneous fission. For PWRs the concentration of uranium must be enriched to around 4%, however other reactor designs such as the CANDU (Canadian deuterium-uranium) reactor can use un-enriched uranium. Weapons grade uranium is generally more than 85% ${}^{235}_{92}U$ but it is possible to make a crude atomic bomb with enrichments as low as 20%. The fact that nuclear reactors use 4% enriched uranium means it is impossible for a reactor to explode like an atomic bomb, although other kinds of problems can occur.

Two other reactor fuels, ${}^{233}_{92}U$ and ${}^{239}_{94}Pu$, do not occur in nature but can be manufactured inside a reactor. The process that creates plutonium starts with the non fissile isotope of uranium: ${}^{238}_{92}U + n \rightarrow {}^{239}_{92}U \rightarrow {}^{239}_{93}Np + \mathrm{e}^{-} + \bar{\nu} \rightarrow {}^{239}_{94}Pu + \mathrm{e}^{-} + \bar{\nu}$. The ${}^{239}_{94}Pu$ then undergoes fission in a manner similar to ${}^{235}_{92}U$. In this way the non fissionable ${}^{238}_{92}U$, which makes up more than 95% of the uranium fuel rod, actually provides most of the fuel for a modern reactor. Placing a layer or blanket of ${}^{238}_{92}U$ or other, non fissionable material around the core of a reactor, before or in place of the reflector, allows neutrons escaping from the core to be used to change this material into fissionable fuel. Such an arrangement is called a breeder reactor. All reactors are breeder reactors to some degree since fissionable fuel is being produced but only those reactors where the produced fuel is removed for use in other reactors are referred to as breeder reactors.

Because isotopes of a particular element all have the same chemical properties the enrichment process for changing uranium from 0.7% ${}^{235}_{92}U$ to 4% or higher is very difficult to carry out. The most common method of enrichment is to gasify the uranium by reacting it with fluoride and allowing it to diffuse through a set of semi-permeable membranes. The slight mass difference between the isotopes means molecules with the lighter isotope will diffuse faster than those with the heavier isotope. Specialized centrifuges and other processes can also be used to take advantage of this small mass difference to separate the two isotopes.

As the $^{235}_{92}U$ in a fuel rod decays, the concentration of $^{235}_{92}U$ eventually decreases to less than 4% and, although only about 1% of the fuel has been used, a chain reaction cannot be sustained. However it is possible to use enrichment processes to capture the $^{235}_{92}U$ and other fissionable material remaining in a fuel rod after it has been used in a reactor in a process known as a closed fuel cycle. Closed fuel cycles are presently used in France and Japan; spent fuel rods are periodically removed from a reactor and the fissionable uranium extracted for use in new fuel rods. Fuel cycles for commercial nuclear power plants in the United States are open; the spent fuel rod material is simply stored rather than recycled. This is done because it is currently economically more cost effective to use new fuel sources rather than recycle spent fuel due to the complexity of the recycling process. In addition, the technological complications involved in the enrichment process have thus far prevented terrorists from making enough enriched uranium for an atomic bomb and some experts fear that if recycling technology were widely spread it would more easily become available to terrorists.

### 4.6.3 RADIOACTIVE WASTE

The three main obstacles currently blocking an expansion of nuclear power in the world are 1) public perception of risk; 2) problems of proliferation of radioactive material to terrorist groups; and 3) the problem of nuclear waste. A consideration of the real and perceived risks of nuclear radiation and nuclear accidents will be discussed in Chapter Eight along with a consideration of the risk of proliferation. Although the majority of nuclear waste found in storage today comes from military defense projects, waste from reactors is also a serious and growing problem [22]. The daughter products from the two fission processes shown in Table 4.6 are only a small sample of such fission products. Half lives for these products range from one year for $^{106}_{44}Ru$ to $2.1 \times 10^5$ years for $^{99}_{43}Tc$. The breeding process mentioned above also creates new radioactive nuclei, both in the uranium fuel, which actually becomes more radioactive than it was to begin with, and in the various metals making up the structure of the reactor which also end up as different isotopes due to neutron bombardment. The half lives of these new heavy nuclei range from 13 years for $^{241}_{94}Pu$ to $2.1 \times 10^6$ years for $^{237}_{93}Np$. These elements are sometimes also chemically reactive and can be poisonous. Clearly a solution of how to keep these byproducts sequestered from humans for very long periods of time is needed.

Radioactive waste can be classified as low level, including material used in hospital treatments and research laboratories; medium level which includes nuclear reactor parts and some material used in industry; and high level which includes spent fuel rods. Various proposals have been made for disposal of nuclear waste including transmuting the material into other radioactive material with shorter half life, recycling the material in a closed fuel cycle and disposal either in ocean trenches or deep geological formations or even into outer space. Currently the only economically feasible disposal is in deep, stable geological structures. The waste is first chemically modified into a chemically stable form such as synthetic rock or glass. The stabilized material is then buried in a dry rock formation such as a salt mine, in a zone where there is not likely to be much earthquake activity. The risk factors associated with nuclear reactors and radioactive waste will be discussed in Chapter Eight.

### 4.6.4 NUCLEAR FUSION

To conclude this section we describe the process of nuclear fusion. It may be noticed that elements lighter than iron also have lower binding energy per nucleon, just as elements heavier than iron do. Lighter elements, however, become more stable by gaining nucleons in a process called fusion rather than by losing nucleons in decay processes. Again some of the mass is turned into energy; the combined nucleons weigh less than the individual components. The main obstacle to fusing lighter nuclei together is the electrical repulsion of the protons in the nucleus. To overcome this repulsion the atoms must be put under enormous pressure and temperature. Two places where this occurs are in the sun and in hydrogen bombs.

The nuclear process which gives stars and hydrogen bombs their energy occurs in several stages but the so called proton-proton cycle can be summarized as

$$6\,{}_{1}^{1}H \rightarrow {}_{2}^{4}He + 2\,{}_{1}^{1}H + 2e^{+} + 2\nu + 2\gamma + 25MeV\ . \qquad (4.10)$$

Heavier elements up to iron can be formed in a star if it is large enough so that pressures and temperatures in the center remain high. Our sun will stop shining after it finishes turning all the hydrogen in the core into helium after which the pressures and temperatures will be too low to fuse heavier elements. This process is expected to take about another 4.5 to 5 billion years to complete. All of the solid material in the universe was initially hydrogen; the heavier elements, such as carbon, iron, etc. of which we are formed, all came from stellar processes. Elements lighter than iron were formed by fusion in large stars which exploded at the end of the fusion process. Elements heavier than iron were formed during the explosion by chance collisions of lighter elements.

There are currently several different experiments underway around the world in an effort to achieve controlled fusion for use as an energy source. Achieving controllable hydrogen fusion would result in a near perfect fuel because, unlike fission, there are no dangerous fuels or waste products and the available energy is limitless for all practical purposes. Although fusion research has been ongoing since the 1950s there are still substantial technical barriers to building a fusion power plant. Current estimates are that fusion may become a possible energy source by 2050.