ENERGY FROM THE NUCLEUS

55.1 Nuclear Reaction

Rutherford suggested in 1919 that a massive particle with sufficient kinetic energy might be able to penetrate a nucleus. The result would be either a new nucleus with greater atomic number and mass number or a decay of the original nucleus. Rutherford bombarded nitrogen (^{14}N) with a particles and obtained an oxygen (^{17}O) nucleus and a proton:

$$_2He^4 \;+\; _7N^{14} \longrightarrow {}_8O^{17} + {}_1H^1$$

Nuclear reactions are subject to several conservation laws. The classical conservation principles for charge, momentum, angular momentum, and energy (including rest energies) are obeyed in all nuclear reactions. An additional conservation law, not anticipated by classical physics, is conservation of the total number of nucleons. The numbers of protons and neutrons need not be conserved separately.

55.2 Reaction Energy

The difference between the masses before and after the reaction corresponds to the reaction energy, according to the mass-energy relationship $E = mc^2$. If initial particles A and B interact to produce final particles C and D, the reaction energy Q is defined as:

$$Q = (m_A + m_B)c^2 - (m_C + m_D)c^2 \quad \text{-------------} \quad (1)$$

Here $m_A = mass\ of\ the\ target\ nucleus$

$m_B = mass\ of\ the\ projectile\ nucleus$

$m_C = mass\ of\ the\ residual\ nucleus$

$m_D = mass\ of\ the\ emerging\ nucleus$

If ‘K’ represents the kinetic energy, then the reaction energy ‘Q’ is given by:

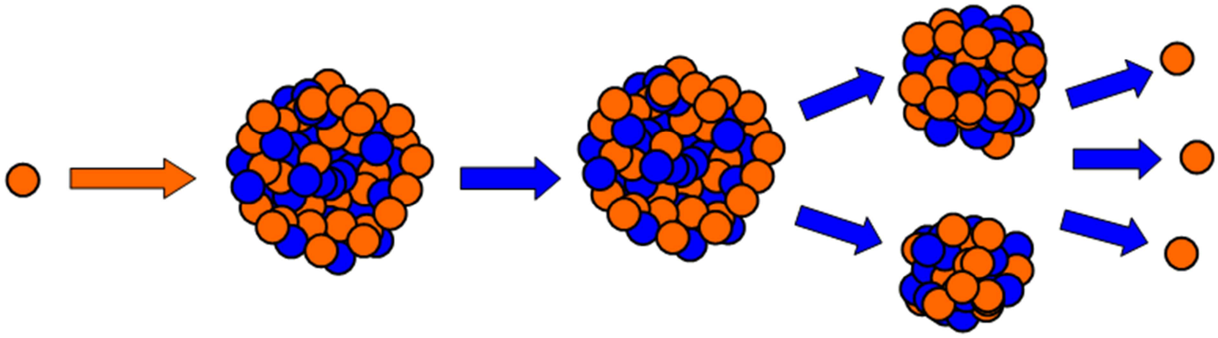
$$Q = (K_C + K_D) - (K_A + K_B) \quad \text{-------------} \quad (2)$$

When Q is positive, the total mass decreases and the total kinetic energy increases. Such a reaction is called an exothermal reaction. When Q is negative, the mass increases and the kinetic energy decreases, and the reaction is called an endothermal reaction.

55.3 Nuclear Fission

Nuclear fission is a decay process in which an unstable nucleus splits into two fragments of comparable mass. Fission was discovered in 1938 through the experiments of Otto Hahn and Fritz Strassman in Germany. Pursuing earlier work by Fermi, they bombarded uranium (z = 92) with neutrons. The resulting radiation did not coincide with that of any known radioactive nuclide. Urged on by their colleague Lise Meitner, they used meticulous chemical analysis to reach the astonishing but inescapable conclusion that they had found a radioactive isotope of barium (Z = 56). Later, radioactive krypton (Z = 36) was also found.

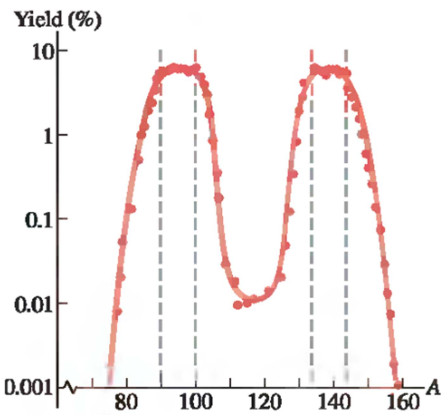
Meituer and Otto Frisch correctly interpreted these results as showing that uranium nuclei were splitting into two massive fragments called fission fragments. Two or three free neutrons usually appear along with the fission fragments.



Both the common isotope (99.3%) ^{238}U and the uncommon isotope (0.7%) ^{235}U (as well as several other nuclides) can be easily split by neutron bombardment: ^{235}U by slow neutrons (kinetic energy less than 1 eV) but ^{238}U only by fast neutrons with a minimum of about 1 MeV of kinetic energy. Fission resulting from neutron absorption is called induced fission. Some nuclides can also undergo spontaneous fission without initial neutron absorption, but this is quite rare.

When ^{235}U absorbs a neutron, the resulting nuclide ^{236}U is in a highly excited state and splits into two fragments almost instantaneously.

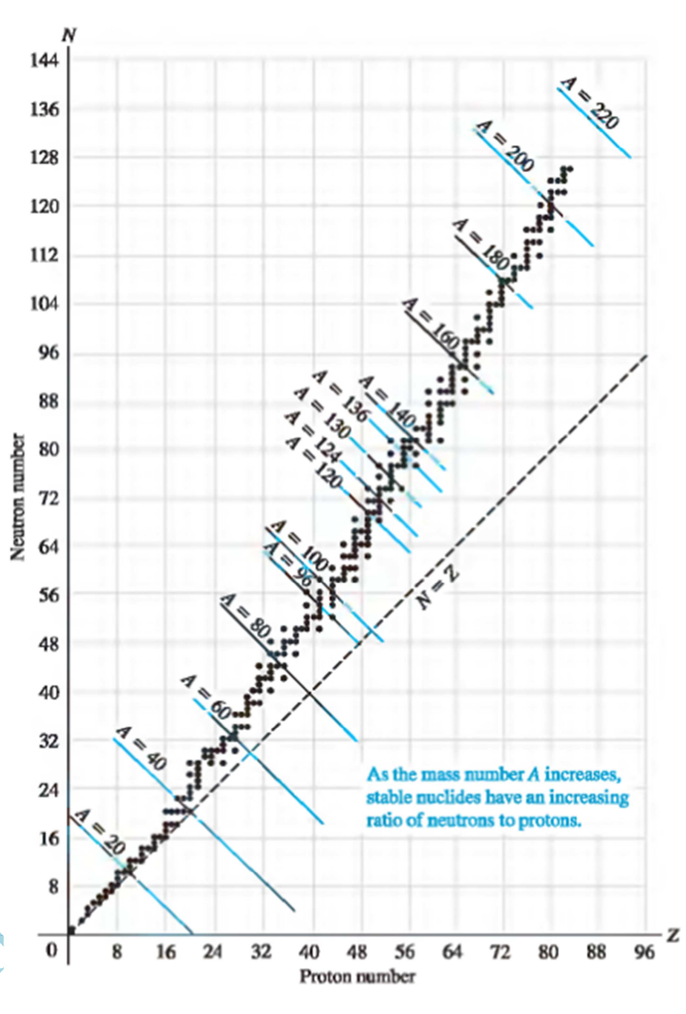
Over 100 different nuclides, representing more than 20 different elements, have been found among the fission products. Figure shows the distribution of mass numbers for fission fragments from the fission of ^{235}U. Most of the fragments have mass numbers from 90 to 100 and from 135 to 145; fission into two fragments with nearly equal mass is unlikely.



Following are the two different nuclear fission reactions:

$$_{92}U^{235} + {_0}n^1 \longrightarrow {_{92}^{*}}U^{236} \longrightarrow {_{56}}Ba^{144} + {_{36}}Kr^{89} + 3{_0}n^1$$

$$_{92}U^{235} + {_0}n^1 \longrightarrow {_{92}^{*}}U^{236} \longrightarrow {_{54}}Xe^{140} + {_{38}}Sr^{94} + 2{_0}n^1$$



The total kinetic energy of the fission fragments is enormous, about 200 MeV (compared to typical α and β energies of a few MeV). The reason for this is that nuclides at the high end of the mass spectrum (near A = 240) are less tightly bound than those nearer the middle (A = 90 to 145). Referring to the binding energy per nucleon curve, the average binding energy per nucleon is about 7.6 MeV at A = 240 but about 8.5 MeV at A = 120. Therefore a rough estimate of the expected increase in binding energy during fission is about 8.5 MeV - 7.6 MeV = 0.9 MeV per nucleon, or a total of (235)(0.9 MeV) = 200 MeV.

Fission fragments always have too many neutrons to be stable. The neutron-proton ratio (N/Z) for stable nuclides is about 1 for light nuclides but almost 1.6 for the heaviest nuclides because of the increasing influence of the electrical repulsion of the protons. The N/Z value for stable nuclides is about 1.3 at A = 100 and 1.4 at A = 150. The fragments have about the same N/Z as ^{235}U, about 1.55. They usually respond to this surplus of neutrons by undergoing a series of β - decays (each of which increases Z by 1 and decreases N by 1) until a stable value of N/Z is reached. A typical example is

$$_{54}Xe^{140} \xrightarrow{\beta^-} {}_{55}Cs^{140} \xrightarrow{\beta^-} {}_{56}Ba^{140} \xrightarrow{\beta^-} {}_{57}La^{140} \xrightarrow{\beta^-} {}_{58}Ce^{140}$$

The nuclide 140Ce is stable. This series of f3 - decays produces, on average, about 15 MeV of additional kinetic energy. The neutron excess of fission fragments also explains why two or three free neutrons are released during the fission.

55.3.1 Bohr Wheeler Theory or Liquid Drop Model

According to Bohr's liquid drop model, a nucleus can be compared with a (charged) liquid drop. Two types of forces play their role. One type of force try to keep the drop intact. They included intermolecular forces of attraction and the surface tension. Collectively they are called cohesive forces.

On the other hand, there are some forces witch try to de-shape the drop and to destroy its structure. they included external forces such as weight of drop. If the drop is charged, then the repulsive forces between charges on drop also try to destroy the structure of the drop. These forces are called destructive forces.

In normal liquid drop, the cohesive forces dominate destructive forces and the drop is stable. But if the charged liquid drop is of bigger size, the cohesive forces are hardly able to balance the destructive forces. And the liquid drop is in a state of highest instability and the surface oscillations will be set-up. A slight provocation may cause splitting of a drop into two or more smaller drops.

Similarly, two types of forces are effective in case of a nucleus:

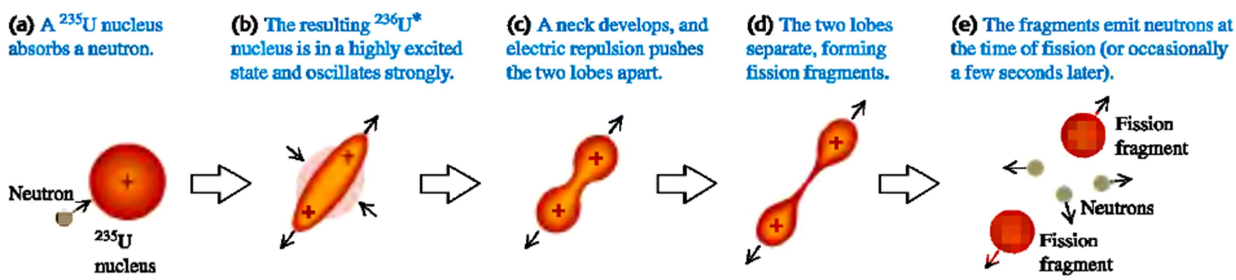
Strong nuclear force between the nucleon: This is a short range force which is attractive in nature. It can be compared with the cohesive forces of the liquid drop model.

Coulomb Repulsive force between protons: These forces are repulsive in nature and play the role of destructive force in nucleus.

In the lighter nucleus, short range nuclear forces dominate coulomb forces of repulsion and so the nucleus is stable. But in the heavy nucleus such as ${}_{92}U^{235}$, short range nuclear forces are hardly able to balance the coulomb repulsive force. So such nucleus is in the state of highest instability.

When the ${}_{92}U^{235}$ nucleus absorbs a slow neutron, the neutron falls into the potential well associated with the strong nuclear force. Its potential energy is converted into excitation energy of the nucleus. the nucleus which has already the surface oscillations, will acquire a dumbbell shape. This excess energy causes violent oscillations, during which a neck between two lobes develops. The electrical repulsion of these two lobes stretches the neck further and finally two smaller fragments are formed that move rapidly apart.

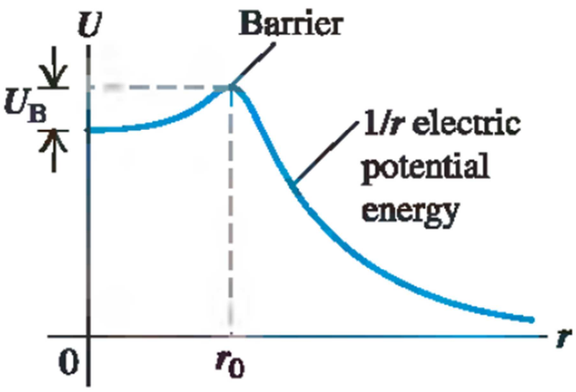
A liquid–drop model of fission.



The sequence of events for a fission reaction is as follows:

1. The ^{235}U nucleus captures a thermal (slow-moving) neutron.
2. The capture results in the formation of 236U*, and the excess energy of this nucleus causes it to undergo violent oscillations.
3. The $^{236}U^{*}$ nucleus becomes highly elongated, and the force of repulsion between protons in the two halves of the dumbbell-shaped nucleus tends to increase the distortion.
4. The nucleus splits into two fragments, emitting several neutrons in the process.

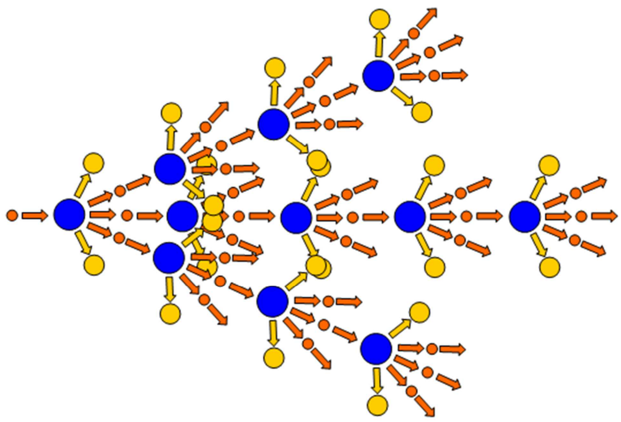
This qualitative picture has been developed into a more quantitative theory to explain why some nuclei undergo fission and others don't. This explanation is given on a hypothetical potential energy function for two possible fission fragments described in the figure below:



If neutron absorption results in an excitation energy greater than the energy barrier height U_B, fission occurs immediately. Even when there isn't quite enough energy to surmount the barrier, fission can take place by quantum-mechanical tunneling. In principle, many stable heavy nuclei can fission by tunneling. But the probability depends very critically on the height and width of the barrier. For most nuclei this process is so unlikely that it is never observed.

55.3.2 Chain Reactions

Fission of a uranium nucleus, triggered by neutron bombardment, releases other neutrons that can trigger more fissions, suggesting the possibility of a chain reaction. The chain reaction may be made to proceed slowly and in a controlled manner in a nuclear reactor or explosively in a bomb. The energy release in a nuclear chain reaction is enormous, far greater than that in any



chemical reaction. (In a sense, fire is a chemical chain reaction.) For example, when uranium is "burned" to uranium dioxide in the chemical reaction:

$$U + O_2 \longrightarrow UO_2$$

The heat of combustion is about 4500 J/g. Expressed as energy per atom, this is about 11 eV per atom. By contrast, fission liberates about 200 MeV per atom, nearly 20 million times as much energy.

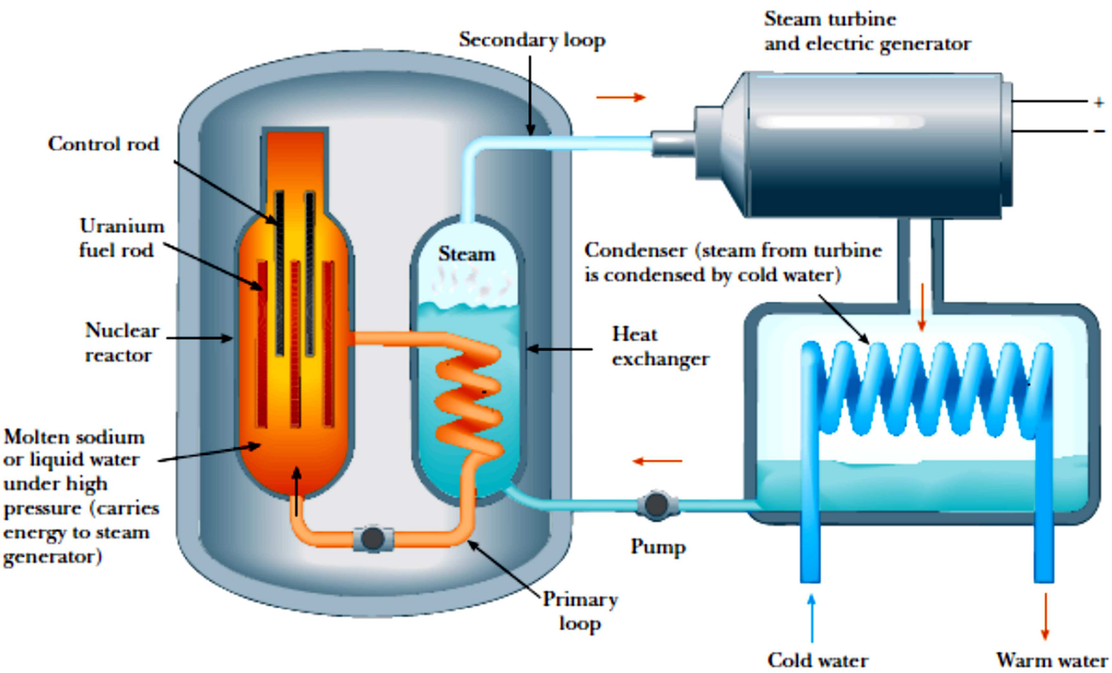
55.4 Nuclear Fission Reactor

A nuclear reactor is a system in which a controlled nuclear chain reaction is used to liberate energy. In a nuclear power plant, this energy is used to generate steam, which operates a turbine and turns an electrical generator.

On average, each fission of a ^{235}U nucleus produces about 2.5 free neutrons, so 40% of the neutrons are needed to sustain a chain reaction. A ^{235}U nucleus is much more likely to absorb a low-energy neutron (less than I eV) than one of the higher-energy neutrons (1 MeV or so) that are liberated during fission. In a nuclear reactor the higher-energy neutrons are slowed down by collisions with nuclei in the surrounding material, called the moderator, so they are much more likely to cause further fissions. In nuclear power plants, the moderator is often water, occasionally graphite. The rate of the reaction is controlled by inserting or withdrawing control rods made of elements (such as boron or cadmium) whose nuclei absorb neutrons without undergoing any additional reaction. The isotope ^{238}U can also absorb neutrons, leading to $^{239}U^*$, but not with high enough probability for it to sustain a chain reaction by itself. Thus uranium that is used in reactors is often "enriched" by increasing the proportion of ^{235}U above the natural value of 0.7%, typically to 3% or so, by isotope-separation processing.

The most familiar application of nuclear reactors is for the generation of electric power. As was noted above, the fission energy appears as kinetic energy of the fission fragments, and its immediate result is to increase the internal energy of the fuel elements and the surrounding moderator. This increase in internal energy is transferred as heat to generate steam to drive turbines, which spin the electrical generators.

The energetic fission fragments heat the water surrounding the reactor core. The steam generator is a heat exchanger that takes heat from this highly radioactive water and generates nonradioactive steam to run the turbines.



Nuclear fission reactors have many other practical uses. Among these are the production of artificial radioactive isotopes for medical and other research, production of high-intensity neutron beams for research in nuclear structure, and production of fissionable nuclides such as ^{239}Pu from the common isotope ^{238}U.

Earlier we mentioned that an average of about 2.5 neutrons is emitted in each fission event of 235U. In order to achieve a self-sustained chain reaction, one of these neutrons must be captured by another 235U nucleus and cause it to undergo fission. A useful parameter for describing the level of reactor operation is the reproduction constant *K*, defined as the average number of neutrons from each fission event that will cause another event. As we have seen, *K* can have a maximum value of 2.5 in the fission of uranium. In practice, however, *K* is less than this because of several factors.

A self-sustained chain reaction is achieved when $K = 1$. Under this condition, the reactor is said to be critical. When *K* is less than one, the reactor is subcritical and the reaction dies out. When *K* is greater than one the reactor is said to be supercritical, and a runaway reaction occurs. In a nuclear reactor used to furnish power to a utility company, it is necessary to maintain a *K* value close to one.

Neutron Leakage

In any reactor, a fraction of the neutrons produced in fission will leak out of the core before inducing other fission events. If the fraction leaking out is too large, the reactor will not operate. The percentage lost is large if the reactor is very small because leakage is a function of the ratio of surface area to volume. Therefore, a critical requirement of reactor design is choosing the correct surface-area-to volume ratio so that a sustained reaction can be achieved.

Regulating Neutron Energies

The neutrons released in fission events are highly energetic, with kinetic energies of about 2 MeV. It is found that slow neutrons are far more likely than fast neutrons to produce fission events in ^{235}U. Further, ^{238}U doesn't absorb slow neutrons. In order for the chain reaction to continue, therefore, the neutrons must be slowed down. This is accomplished by surrounding the fuel with a substance called a moderator.

Neutron Capture

In the process of being slowed down, neutrons may be captured by nuclei that do not undergo fission. The most common event of this type is neutron capture by ^{238}U. The probability of neutron capture by ^{238}U is very high when the neutrons have high kinetic energies and very low when they have low kinetic energies. The slowing down of the neutrons by the moderator serves the dual purpose of making them available for reaction with ^{235}U and decreasing their chances of being captured by ^{238}U.

55.4.1 Control of Power Level

It is possible for a reactor to reach the critical stage (K= 1) after all neutron losses described previously are minimized. However, a method of control is needed to adjust K to a value near one. If K were to rise above this value, the heat produced in the runaway reaction would melt the reactor. To control the power level, control rods are inserted into the reactor core. These rods are made of materials such as cadmium that are highly efficient in absorbing neutrons. By adjusting the number and position of the control rods in the reactor core, the K value can be varied and any power level within the design range of the reactor can be achieved.

Fission events in the reactor core supply heat to the water contained in the primary (closed) system, which is maintained at high pressure to keep it from boiling. This water also serves as the moderator. The hot water is pumped through a heat exchanger, and the heat is transferred to the water contained in the secondary system. There the hot water is converted to steam, which drives a turbine–generator to create electric power.

55.5 Nuclear Fusion

The biding energy per nucleon curve described that the energy can be released if light nuclei are combined to form nuclei of larger mass number. When two light nuclei combine to form a heavier nucleus, the process is called nuclear fusion. Because the mass of the final nucleus is less than the masses of the original nuclei, there is a loss of mass, accompanied by a release of energy.

However the process of nuclear fusion is hindered by the mutual Coulomb's repulsion that tends to prevent two such (positively) charged particles from coming within range of each other's attractive nuclear force. Thus the nucleons have to overcome the potential barrier in order to make the nuclear fusion.

In case of the alpha decay, two charged particles − the alpha particle and the residual nucleus − are initially inside their mutual potential barriers. For alpha decay to occur, the alpha particle must leak through the barrier through barrier tunneling process and appear on outside. In nuclear fusion, the situation is just reversed. Here the two particles must penetrate their mutual barrier from the outside. for the case of the fusion of deuterons, the particles have to penetrate through the potential barrier of 200 keV. One way to arrange for the nuclei to penetrate their mutual Coulomb barrier is to use one light particle as a target and to accelerate other by using cyclotron. But this technique is not useful for obtaining the energy in a controlled manner. The best hope for obtaining the fusion in bulk matter in controlled fashion is to raise the temperature of the material, so that that the particles have sufficient energy to penetrate the barrier due to their thermal motion. This process is called thermonuclear fusion.

The mean thermal kinetic energy $\overline{K}$ of the particle in equilibrium at a temperature T is given by the expression

$$\overline{K} = \frac{3}{2}kT$$

Where k is the Boltzmann constant.

55.6 Thermonuclear Fusion in Stars

The composition of the sun's core is about 35% hydrogen by mass, about 65% helium and about 1% other elements. The temperature at the center of the sun is about $1.5\times10^{7}K$. At this temperature, the light elements are essentially totally ionized. The sun radiates at the rate of $3.9\times10^{26}W$ and has been doing so for as long as the solar system has existed, which is about 4.5×10^{9} years.

The Sun's energy is generated by the thermonuclear fusion of hydrogen to form helium. The thermonuclear fusion by the proton-proton cycle is described as follows:

$$\boxed{{}^1H + {}^1H \rightarrow {}^2H + e^+ + \nu \ \ (Q = 0.42 MeV)} \qquad \boxed{{}^1H + {}^1H \rightarrow {}^2H + e^+ + \nu \ \ (Q = 0.42 MeV)}$$

$$\boxed{e^- + e^+ \rightarrow \gamma + \gamma \ \ (Q = 1.02\, MeV)} \qquad \boxed{e^- + e^+ \rightarrow \gamma + \gamma \ \ (Q = 1.02\, MeV)}$$

$$\downarrow \qquad\qquad\qquad\qquad \downarrow$$

$$\boxed{{}^2H + {}^1H \rightarrow {}^3He + \gamma \ \ (Q = 5.49 MeV)} \qquad \boxed{{}^2H + {}^1H \rightarrow {}^3He + \gamma \ \ (Q = 5.49 MeV)}$$

$$\downarrow \qquad\qquad\qquad\qquad \downarrow$$

$$\downarrow$$

$$\boxed{{}^3He + {}^3He \rightarrow {}^4He + {}^1H + {}^1H \ \ \ (Q = 12.86 MeV)}$$

The cycle is initiated by the collision of two protons (${}^1H + {}^1H$) to form a deuteron (${}^2H$) with the simultaneous creation of positron and a neutrino. The positron very quickly encounters a free electron (e^-) in the sun and both particles annihilates, their rest energies appearing as two γ-ray photons. Such events are extremely rare. In fact, only once in about 10^{26} proton-proton collisions a deuteron formed. In vast majority of cases, the colliding protons simply scatter from each other. It is the slowness of this process that regulates the rate of energy production and keeps the sun from exploding. Inspite of this slowness, there are so very many proton in the huge volume of the sun's core that deuterium is produced in this way at the rate of about $10^{12}\ kg/s$.

Once the deuteron has been produced, it quickly (within a few seconds) collides with another proton and forms a ${}^3He$ nucleus. Two such ${}^3He$ nuclei may then eventually collide, forming an alpha particle (${}^4He$) and two protons.

Taking an overall view of the proton-proton cycle, we see that it amounts to the combination f four protons and two electrons to form an alpha particle, two neutrinos, and six gamma rays:

$$4\,{}^1H + 2e^- \rightarrow {}^4He + 2\nu + 6\gamma$$

Now in formal way, by adding two electrons to each side of above equation yields:

$$4\,({}^1H + e^-) \rightarrow ({}^4He + 2e^-) + 2\nu + 6\gamma$$

The quantities in the parenthesis represent the atoms (not bare nuclei) of hydrogen and helium. The energy released in this whole process can be fond out by using the atomic masses of hydrogen and helium.

$$Q = \Delta m\, c^2 = [4m({}^1H) - m({}^4He)]c^2$$

$$= [4(1.007825\,u) - 4.002603\,u](931.5\, MeV/u)$$

$$Q = 26.7\, MeV$$

Neutrino and gamma-ray photons have no mass and thus do not enter into the calculation of disintegration energy.

If the core temperature heats upto about $10^8\ K$, energy can be released by burning helium to make carbon.

$$^4He + ^4He + ^4He \rightarrow ^{12}C + \gamma \quad (Q = 7.3 MeV)$$

As a star evolves and becomes still hotter, other elements can be formed by other fusion reactions. However the elements beyond $A = 56$ cannot be manufactured by futher fusion process. The elements with $A = 56$ (^{56}Fe, ^{56}Co, ^{56}Ni) lie near the peak of the binding energy per nucleon curve, and the fusion between nuclides beyond this point involves consumption, and not the production, of energy.

55.7 Controlled Nuclear Fusion

Thermonuclear reactions have been going on in the universe since its creation. Such reactions have been taken place on earth, however, only since October 1952, when the first fusion (or hydrogen) bomb was exploded. The high temperature needs to initiate the thermonuclear reaction in this case were provided by fission bomb used as a trigger.

A sustained and controllable thermonuclear power source (fusion reactor) is proving much more difficult to achieve. The goal, however, is being vigorously pursued because many look to the fusion reactor as the ultimate power source of the future, at least as for as the generation of electricity is concerned.

The proton-proton interaction is not suitable for use in a terrestrial fusion reactor because this process is hopelessly slow. The reaction cross-section is in fact so small that it cannot be measured in the laboratory. The reaction succeeds under the condition that prevail in stellar interiors only because of the enormous number of protons available in the high density stellar cores.

The most attractive reactions for terrestrial use appear to be the deuteron-deuteron (d-d) and deuteron-triton (d-t) reactions:

$$^2H + ^2H \rightarrow ^3He + n \qquad (Q = 3.27\ MeV)$$

$$^2H + ^2H \rightarrow ^3H + ^1H \qquad (Q = 4.03\ MeV)$$

$$^2H + ^3H \rightarrow ^4He + n \qquad (Q = 17.59\ MeV)$$

Deuteron whose natural abundance in normal hydrogen is 0.015 %, is available in unlimited quantities as a component of sea water. Tritium is a radioactive and is not normally found in naturally occurring hydrogen.

55.8 Requirements for a Thermonuclear Reactor

There are three basic requirements for the successful operation of a thermonuclear reactor.

1. **A high particle density n**

   The number of interacting particles (deuterons) per unit volume must be great enough to ensure a sufficiently high deuteron-deuteron collision rate.

2. A High Plasma Temperature T

High temperature is required, so that the deuterium gas would be completely ionized into natural plasma consisting of deuterons and electrons. Moreover the colliding deuterons should be energetic enough to penetrate the mutual Coulomb's barrier. A plasma temperature of $2.8\times10^{8}\,K$, corresponding to kinetic energy of 33 KeV, has been achieved in laboratory.

3. A Long Confinement Time

A major problem is containing the hot plasma to ensure that its density and temperature remains sufficiently high. It is clear that no actual solid container can withstand with the high temperatures, so the special techniques must be employed

55.8.1 Lawson's Criterion

For the successful operation of a thermonuclear reactor to have

$$nT \geq 10^{20}\ s.m^{-3}$$

This condition is called Lawson's criterion. This condition tells that we have a choice between confining a lot of particles for a relatively short time or confining fewer particles for a somewhat longer time. Beyond meeting this criterion, it is also necessary that the plasma temperature be sufficiently high.

There are two techniques that have been used to attempt to achieve the combination of temperature T and Lawson's parameter nT that are necessary to produce fusion reactions.

1. Magnetic confinement uses magnetic fields to confine the plasma while its temperature is increased.
2. In inertial confinement, a small amount of fuel is compressed and heated so rapidly that fusion occurs before the fuel can expand and cool.

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