FISSION REACTORS AND FUSION

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FISSION REACTORS

The two important aspects by which nuclear fission differs from other nuclear reactions are the following:

1. In each fission more than one neutron is produced for each neutron absorbed. In the fission of U^{235} by thermal neutrons, for example, 2.5 neutrons, on the average, are emitted in each fission. This means that under proper conditions the fission can be made a self-sustaining reaction, and a chain reaction is possible.

2. In each fission about 200 MeV of energy is released, most of which (~ 165 MeV) is carried away by the fission fragments. This energy is available in the form of heat and may be utilized for the purpose of power production.

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Fission nuclear-reactors are made possible for power production by utilizing these two characteristics. The self-sustained chain reaction is possible only if the number of neutrons produced in a given generation are more than, or equal to, the previous generation. An important quantity k, called the *reproduction factor or multiplication factor*, is defied as,

$$k = \frac{number\ of\ \ neutrons\ \text{in}\ the\ (n+1)th\ generation}{number\ of\ \ neutrons\ in\ the\ nth\ generation} \qquad (1)$$

If the number of neutrons produced in any generation is equal to that of the previous generation, or if $k=1$, the system is said to be *critical*. On the other hand, if $k<1$, that is, the number of neutrons in any generation is less than that in the previous generation, the system is said to be *subcritical* or *convergent.*

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The system in which $k>1$, the number of neutrons in any generation is more than that in the previous generation, is called *supercritical or divergent*. In order to obtain a continuous, uniform supply of power from a fission reactor, the system must be critical. For a supercritical system the power will continuously increase, and it finally will become uncontrollable.

In a subcritical system the power will continuously decrease and the system will eventually reduce the power level to zero. In a nuclear reactor, initially k is made slightly greater than unity, and after the desirable power level is reached, k is maintained at unity. The aim of a reactor designer, therefore, is to achieve a critical system.

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The nucleus U^{235} is the only one occurring naturally that is fissionable by thermal neutrons. Natural uranium is a combination of the isotopes U^{235} and U^{238} in the ratio 1:138, which means that the abundance of U^{235} in natural uranium is only 0.71 percent by weight.

Because of the identical chemical properties of the two isotopes, separation of U^{235} from U^{238} is a costly process. It is accomplished by making use of the small difference in their diffusion rates. It is not possible to achieve a critical system by using natural uranium for fission, because neutrons are absorbed in nonfission processes both in U^{235} and U^{238}.

These processes can be understood by considering the life history of a neutron produced in fission.

LIFE CYCLE OF NEUTRONS PRODUCED IN FISSION

Neutrons produced in fission may have energies anywhere from thermal to about 18 MeV. Let us consider a representative group of fast neutrons produced in fission and see what may happen to them in their subsequent life times. Because we are interested in producing fission of U^{235} by thermal neutrons, it is necessary to slow these neutrons to thermal energies by using some moderator (such as water, heavy water, or carbon) with the fissionable material.

We shall consider the life cycle of a single fast neutron of a given energy group.

LIFE CYCLE OF NEUTRONS PRODUCED IN FISSION

1. ***Fast Fission (ε).*** Because U^{238} is fissionable by fast neutrons, there is some probability that the fast neutron will cause fission. This probability is denoted by *ε,* called the *fast-fission factor*. Starting with one neutron, therefore, we have ($\varepsilon > 1$) neutrons.
2. ***Fast Nonleakage (P_f).*** In the process of slowing down there is some chance that the fast neutrons will leave the system. If P_f represents the *fast nonleakage probability*, we shall be left with εP_f neutrons at the end, while $\varepsilon(1-P_f)$ will leave the system.
3. ***Resonance Escape (p).*** U^{238} has several very strong resonance peaks in the energy range from 5 eV to 200 eV. Thus, before reaching thermal energies, some fraction of εP_f neutrons will be absorbed by these resonance absorptions. Let us call *p* the *resonance-escape probability*. On the average, $\varepsilon P_f p$ neutrons will reach thermal energies escaping resonance absorption. The fraction absorbed in the resonance peaks is $\varepsilon P_f(1-p)$.

LIFE CYCLE OF NEUTRONS PRODUCED IN FISSION

4. ***Thermal Nonlekage (P_t).*** On the average, we have now $\varepsilon P_f p$ neutrons at thermal energies. Before these neutrons are absorbed in fissionable and nonfissionable processes, there is some probability that a fraction of them will leave the system. If we represent the *thermal nonleakage-probability* by P_t , we will be left with $\varepsilon P_f pP_t$ thermal neutrons available for absorption. The number of neutrons that leave the system at thermal energies is, thus, $\varepsilon P_f p(1- P_t)$

5. ***Thermal Utilization (f).*** Not all the $\varepsilon P_f pP_t$ neutrons will be absorbed by uranium. A fraction of them will be lost by absorption in the moderating material, shielding, or other things. The fraction not lost in this way is denoted by f and is called the *thermal utilization factor*. The number of neutrons absorbed by uranium, therefore, is $\varepsilon P_f pP_t f$, while the average number of neutrons absorbed by materials other than uranium is $\varepsilon P_f pP_t (1-f)$.

LIFE CYCLE OF NEUTRONS PRODUCED IN FISSION

Fission. $\varepsilon P_f \, p P_t \, f$ thermal neutrons are absorbed by uranium. If ν represents the number of neutrons produced in a fission of U^{235} by a thermal neutron ($\nu \approx 2.5$ in this case), then the number of neutrons, η , produced per thermal neutron absorbed by uranium is given by,

$$\eta = \nu \frac{\sigma_f}{\sigma_f + \sigma_a} \qquad (2)$$

where σ_f represent the fission cross section and σ_a the cross section for other absorptive processes (both of these cross sections are evaluated for thermal neutrons). It is clear that $\eta < \nu$, for some of the original thermal neutrons do not cause fissions.

For ^{235}U, $\sigma_f = 584$ b and $\sigma_a = 97$ b, so that $\eta = 2.08$ fast neutrons are produced per thermal neutron. ^{238}U is not fissionable with thermal neutrons, and so $\sigma_f = 0$, but $\sigma_a = 2.75$ b.

LIFE CYCLE OF NEUTRONS PRODUCED IN FISSION

For a natural mixture of ^{235}U and ^{238}U, the effective fission and absorption cross sections are

$$\sigma_f = \frac{0.72}{100}\sigma_f(235) + \frac{99.28}{100}\sigma_f(238) = 4.20\,b \quad (3)$$

$$\sigma_a = \frac{0.72}{100}\sigma_a(235) + \frac{99.28}{100}\sigma_a(238) = 3.43\,b \quad (4)$$

and the effective value of η becomes 1.33

Thus for each fast neutron the total number of neutrons available at the end of the cycle is $\varepsilon P_f \, p P_t \, f \, \eta$ and is called the *effective reproductive constant* of the reactor,

$$k_{eff} = \eta \, \varepsilon \, p \, f \, P_t \, P_f \quad (5)$$

This is called the *6-factor formula*. It may be noticed that the factors η and ε are each greater than unity, while all the other four, p, f, P_t, and P_f are each less than unity.

LIFE CYCLE OF NEUTRONS PRODUCED IN FISSION

Also η, ε, *p* and *f* depend only on the properties and configuration of the reactor materials (fission fuel and moderator), while P_t and P_f depend upon the internal geometrical configuration and the overall size and shape of the reactor.

If we assume that the overall size of the reactor is infinite, the total nonleakage probability, $P = P_t\ P_f$, will be equal to unity ($P_t = P_f = 1$).

$$k_\infty = \eta\, \varepsilon\ p\ f \qquad (6)$$

where k_∞ is called the *infinite reproductive constant*. Thus

$$k_{eff} = k_\infty P \qquad (7)$$

The design of a nuclear reactor is based on the 6-factor formula.

DESIGN OF A NUCLEAR REACTOR

The goal of a nuclear reactor designer is to adjust the six factors in such a way that $k_{eff} \geq 1$. As an example, we shall discuss the design of a nuclear reactor that uses thermal neutrons. If the reactor fuel is natural uranium, it is not possible to achieve a chain reaction by using high or intermediate energy neutrons because of the high resonance absorption cross-section of U^{238}. If the fast neutrons are allowed to slow down past the resonances without much absorption, a chain reaction is possible by thermal neutrons.

In order to achieve rapid slowing down of the fast neutrons, a material of low mass number is used as moderator with uranium. One may think that a high degree of slowing down will be achieved if uranium is mixed uniformly with the moderator. It is found that a divergent chain reaction is not possible because the resonance absorption of U^{238} is still very high. The uniform mixing of the moderator with the fuel increases the absorption by the moderator as well.

DESIGN OF A NUCLEAR REACTOR

A divergent chain reaction, therefore, is not possible in a *homogeneous thermal reactor* using natural uranium.

A divergent chain reaction is possible with natural uranium only, if the reactor is of the *heterogeneous thermal reactor* type. In this kind of reactor, discrete lumps of uranium in the form of rods form a lattice in a matrix of the moderating material as shown in Fig 14.17 in Fundamentals of Nuclear Physics by Atam P. Arya.

This arrangement has an advantage that fast neutrons produced by fission in the rod leave the rod and are slowed down in the surrounding moderating material. The resonance absorption in U^{238} is reduced by a large amount because only the U^{238} on the surface of the rod is available. After being slowed down, the neutrons can easily go inside the fuel and produce fission, and a divergent chain reaction is produced.

DESIGN OF A NUCLEAR REACTOR

The homogeneous thermal reactors are only possible with uranium enriched with the isotope U^{235}. It may appear that increasing the physical size of the reactor has an advantage because it makes P equal to unity. This advantage is offset by the fact that the size increases absorption in the nonfissionable materials and reduces f considerably. f varies, therefore, in exactly the opposite way to P with fuel element size and spacing. A compromise is made and a value of $P \approx f = 0.95$ is suitable for reactors using natural uranium with heavy water moderators.

The amount of power available from a nuclear reactor is tremendous. Each fission of U^{235}, for example, produces 200 MeV of energy, on the average, or $3.2\text{x}10^{-11}$ watt sec. One gram of U^{235}, if completely fissioned, will produced $8.2\text{x}10^{10}$ watt sec $\approx$ 1 MWD (mega watt days).

DESIGN OF A NUCLEAR REACTOR

As compared to this, one ton of coal produces ~ 0.36 MWD of heat. We may conclude that

1 ton of uranium = 2.7×10^6 tons of coal

An outline of a typical nuclear power plant is shown in Fig. 14.18 in Fundamentals of Nuclear Physics in Atam P. Arya. The heat produced in the reactor core is taken away by the coolant, which, in turn, is used to produce steam. The steam runs a turbine and the electricity is made available through the generator.

For the sake of convenience, nuclear reactors may be classified under two categories upon the type of neutrons used for fission and the purpose of the reactor.

DESIGN OF A NUCLEAR REACTOR

A. Chain Reaction

i. *Fast reactors* are those in which fission is produced by neutrons of energies greater than 0.2 MeV

ii. *Intermediate reactors* are those in which fission is produced by neutrons of energies between 0.1 eV and 0.2 MeV.

iii. *Thermal reactors* are those in which fission is caused by thermal neutrons (of energies less than 0.1 eV)

DESIGN OF A NUCLEAR REACTOR

B. Purpose

i. *Power* for industrial and everyday use

ii. *Research* uses are many and varies. Neutron and gamma beams produced in nuclear reactors, for example, are used in nuclear physics

iii. *Production of fissile material*: U^{233} and Pu^{239}, which do not occur naturally, but which are fissionable, may be produced through the following reactions from Th^{232} and U^{238}, respectively.

$$Th^{232} + n \rightarrow Th^{233} \xrightarrow{\beta^-(22\ \text{min})} Pa^{233} \xrightarrow{\beta^-(27\ days)} U^{233}$$

$$U^{238} + n \rightarrow U^{239} \xrightarrow{\beta^-(23\ \text{min})} Np^{239} \xrightarrow{\beta^-(2.3\ days)} Pu^{239} \qquad (8)$$

Isotopes such as U^{238} and Th^{232}, which can be converted to thermally fissile material, are called *fertile*.

DESIGN OF A NUCLEAR REACTOR

C. Reactor Control

One of the most difficult problems of the nuclear reactor is its control. For this purpose cadmium rods, the control rods, are inserted into the core of the reactor. Because cadmium has a very high absorption cross-section for neutrons, the rods may be adjusted to expose less or more of their length so that the corresponding neutron production rate can be increased or decreased. The rate of increase depends on the time lapse between the successive generations, which may be represented by τ. If the number of neutrons at time $t=0$ is n_0, the number n at any subsequent time will be given by

$$n = n_0 \, e^{(k-1)\, t/\tau} \qquad (9)$$

where $k(=k_{eff})$ of the system determines the neutron population with time. If $k=1$, $n=n_0$, and the power level remains constant.

DESIGN OF A NUCLEAR REACTOR

C. Reactor Control

Suppose it is required to increase the power level. This will require the control rods being pulled out to make k >1. The slowing down time of the fast neutrons is $\tau \sim 10^{-3}$ *sec*. The time allowed to raise the power level and then to maintain it at that level is too small for any mechanical arrangement to control the divergent reaction without letting the reactor run wild and explode.

But the presence of a small fraction of delayed neutrons makes this mechanical control by *Cd* rod possible. Thus if *d* is a fraction of delayed neutrons produced in fission, then *k* may be divided into two parts: *kd* due to delayed neutrons, and *k(1-d)* due to prompt neutrons.

If *k(1-d)* is less than unity, the increase in the number of neutrons is determined by the delayed neutrons for which the effective weighted average gives $\tau=0.1$ sec. This time is large enough for mechanical controls to operate the reactor.

FUSION

Nuclear fusion is just the opposite of nuclear fission. In nuclear fusion, two very light-weight nuclei ($A \leq 8$) combine together to form a heavy nucleus. The heavy nucleus, so formed, has much more binding energy than the combined binding energies of the two light nuclei. This results in conversion of some rest mass into energy, which, under special circumstances, may be made available.

The energy radiated from the sun and the stars is the result of fusion reactions taking place in them. Because of very high temperatures inside the sun and other stars ($\sim 10^8\ {}^0K$), the atoms of the elements are completely ionized. A collection of bare nuclei and electrons are said to form a *plasma*. At such high temperatures the nuclei have very high velocities, and in the process of colliding can very easily cross the coulomb barrier. Thus the cross sections for nuclear fusion are very high, and because the reactions are exoergic, large amounts of energy are available.

FUSION

The reactions that take place by virtue of the very high temperatures are called *thermonuclear reactions*.

There are many different thermonuclear reactions that continuously take place inside the stars. The two most common cycles are the following:

Proton-proton cycle

$$H^1 + H^1 \rightarrow H^2 + \beta^+ + \nu + 0.42\ MeV$$

$$H^2 + H^1 \rightarrow He^3 + \gamma + 5.49\ MeV$$

$$He^3 + He^3 \rightarrow He^4 + 2H^1 + 12.86\ MeV$$

FUSION

Carbon cycle

$$C^{12} + H^{1} \rightarrow N^{13} + \gamma \quad +1.95\,MeV$$

$$N^{13} \rightarrow C^{13} + \beta^{+} + \nu \quad +1.20\,MeV$$

$$C^{13} + H^{1} \rightarrow N^{14} + \gamma \quad +7.55\,MeV$$

$$N^{14} + H^{1} \rightarrow O^{15} + \gamma \quad +7.34\,MeV$$

$$O^{15} \rightarrow N^{15} + \beta^{+} + \nu \quad +1.68\,MeV$$

$$N^{15} + H^{1} \rightarrow C^{12} + He^{4} + 4.96\,MeV$$

The amount of energy available in each of the above cycles is about 20 MeV. The study of fusion has been undertaken to utilize thermonuclear reactions in laboratories and to harness the available energy for useful purposes. There are many difficulties involved-primarily the containment of the plasma at temperatures of the order of $10^{8}\ {}^{0}$K.

FUSION

As an energy source, fusion has several obvious advantages over fission: the light nuclei are plentiful and easy to obtain, and the end products of fusion are usually light, stable nuclei rather than heavy radioactive ones. There is one considerable disadvantage, however: before light nuclei can be combined, their mutual Coulomb repulsion must be overcome.

The possible fusion reactions that use isotopes of hydrogen (deuterium, H^2, and tritium, H^3) are the following:

$${}_1H^2 + {}_1H^3 \rightarrow He^4 + n \quad +17.6\,MeV \quad (\textit{D}\text{euterium-Tritium or D-T reaction})$$

$${}_1H^2 + {}_1H^2 \rightarrow He^3 + n \quad +3.2\,MeV \quad (\textit{D}\text{euterium-Deuterium or D-D reactions})$$

$${}_1H^2 + {}_1H^2 \rightarrow H^3 + H^1 \quad +4.0\,MeV \quad (\textit{D}\text{euterium-Deuterium or D-D reactions})$$

See Fig. 14. 19. in Fundamentals of Nuclear Physics by Atam P. Arya for the cross sections of the first two reactions, which are the most intensively studied.

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If the incident particles have negligibly small kinetic energies, the ^4He and *n* share 17.6 MeV consistent with linear momentum conservation, and a monoenergetic neutron with energy 14.1 MeV emerges.

This reaction often serves as a source of fast neutrons. Because of the large energy release (and because the Coulomb barrier is no higher than in the D-D reactions), the D-T reaction has been selected for use in controlled fusion reactors.

There are many technical problems involved in achieving a controlled thermonuclear reaction. Unlike fission, where no initial heating is needed, fusion requires very high temperatures and confinement of the plasma becomes difficult. The *ignition temperature* is defined as that at which the nuclear power released becomes equal to the power lost due to *Bremsstrahlung*.

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Above this temperature the reaction not only sustains itself, it also releases extra energy.

See Figure 14.17 in Introductory Nuclear Physics by Kenneth S. Krane for comparison of bremsstrahlung losses with power outputs of D-D and D-T reactions.

It can be see that from the Figure 14.17, there is a temperature at which the fusion output will exceed the bremsstrahlung loss, which is of the order of *4* keV for D-T and *40* keV for D-D reactions. This suggests the superiority of the choice of D-T for fuel. Note also that the bremsstrahlung losses increase as Z^2; therefore fusion reactions using nuclei other than hydrogen have substantially greater bremsstrahlung losses as well as generally smaller reaction rates in the keV region (because of the Coulomb barrier).

FUSION

The self-sustaining nuclear reaction is only possible if a minimum temperature of about 10^8 ^{0}K is achieved, and there are two more considerations.

- First, how long does the plasma have to be maintained at this temperature before it becomes self-sustaining?
- Second, what type of materials are we going to use for the walls that confine the plasma?

The answer to the first problem is simple. In practice, containment times of the order of 1/10 and 10 sec are enough.

As for the second question, at present no suitable material is available for the walls. At such high temperatures, any material vaporises, permitting the plasma to disperse.

FUSION

The alternative for a containment material is to confine the plasma at the center of a wide tube by means of external magnetic fields. The method is currently in experiment. The magnetic field confines the plasma by means of the *pinch effect*.

The simplest magnetic confinement is a uniform magnetic field- charged particles spiral about the field direction. This is sufficient to confine the particle in only two directions. To prevent the loss of particles along the axis, there are two solutions shown: we can form a torus, thus keeping the spiral in a ring, or we can form a high density of magnetic field lines which reflects the particles back into the low-field region and is hence known as a *magnetic mirror.* In any real toroidal winding, the field is weaker at larger radii, and thus as a particle spirals it sees a region of lower field which lets the spiral radius become larger and lets the particle approach the outer wall.

FUSION

It can be achieved using a set of external coils, as illustrated in Figure 14.9 by Introductory Nuclear Physics by Kenneth S. Krane, or by passing a current along the axis of the toroid through the plasma itself. The current serves the dual purpose of heating the plasma and confining the particles. The basic design is called a *tokamak* after the Russian acronym for the device.

The tokamak is at present one of the two most promising candidates for the basic design of a fusion power reactor. In actual tokamak developmental facilities, the poloidal field is provided not by a set of external coils (which are used in a different device, known as a *stellerator*), but by a current induced in the plasma itself by a set of external windings that function in essence as the primary of a transformer.

In southern France, 35 nations are collaborating to build the world's largest tokamak, a magnetic fusion device, ITER Tokamak.

For more information https://www.iter.org

REFERENCES

1. Introductory Nuclear Physics. Kenneth S. Krane

2. Fundamentals of Nuclear Physics. Atam. P. Arya