Nuclear Theory - Course 127

NEUTRON REACTIONS

Nuclear reactions can occur as a result of collisions between various particles or gamma photons and nuclei. Nuclear charges particles, such as protons, deuterons (deuterium or H^2) and alpha particles, need to have a large amount of energy (tens of MeV) before they are able to overcome the Coulomb repulsive forces and enter a nucleus.

Neutrons and gamma photons, however, are not charged and are therefore able to interact with nuclei very effectively, even when they have very little energy. In fact, generally speaking, there is a greater chance of a reaction occurring with low rather than high energy neutrons, because the former are in contact with the nucleus for a greater length of time.

The operation of a reactor basically depends on how neutrons react with nuclei in the reactor. It is therefore necessary to look at these reactions, called *neutron reactions*, in some detail. Although there are well over a dozen known neutron reactions, we need only consider the five that are of importance to us.

All neutron reactions can be categorized as either *elastic* or *inelastic collisions*, depending on whether kinetic energy is conserved in the collision or not.

Elastic Collisions

Elastic collisions are those in which the total kinetic energy before the collision is equal to that after the collision.

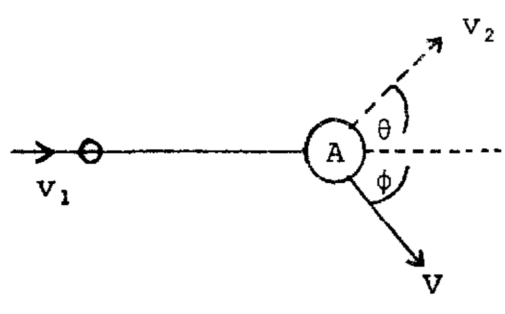

Fig. 1. Neutron Making an Elastic Collision

For example, consider a neutron of mass 1 amu and velocity v, striking a stationary nucleus of mass A amu, and bouncing off with velocity v_2. Since kinetic energy is conserved, we can say that

$$v_1^2 = v_2^2 + AV^2$$

You can see that some of the neutron's energy has been transferred to the target nucleus, the net result being a slowing down of the neutron. In fact, you should be able to show (from conservation of momentum) that the energy lost by the neutron in the collision, ΔE, is given by

$$\frac{\Delta E}{E} = \frac{4A\cos^2\phi}{(A+1)^2}$$

The importance of this expression will become evident later on when we discuss moderators and their properties.

The neutron is said to be *scattered* in the collision process, because the angle θ at which it bounces off the target nucleus depends on the angle at which it strikes it, and obviously this is quite random. Such reactions are therefore described by the term *elastic scattering*.

Inelastic Collisions

The neutron may enter the nucleus to form a *compound nucleus*. This is known as an inelastic collision, because kinetic energy is not conserved. Instead some of the neutron's kinetic energy is transformed into internal energy of the compound nucleus. The compound nucleus has too much energy to exist for any great length of time (no more than 10^{-14}s), and the reaction that then follows will be one of a number of possible alternatives.

1. The compound nucleus may get rid of its excess energy by emitting a neutron and a gamma photon. An example of this is shown in Fig. 2 on the following page. A neutron is shown entering a U-238 nucleus to form a U-239 nucleus. This emits a neutron (any one) and a gamma photon to become U-238 again. The net re-result again is a slowing down of the neutron, because the net energy it has lost has been transferred to the gamma photon. This reaction is known as *inelastic scattering*, because the direction of the emitted neutron is quite arbitrary. The reaction cannot occur unless the compound nucleus has gained sufficient energy to be raised to an excited state, ie, 0.1 MeV for heavy nuclei and much more for lighter ones. From a reactor physics point of view, we can probably ignore inelastic scattering other than with uranium atoms in the fuel where the neutron energies will be greatest.

elastic - same n' (bounces)
inelastic - diff. n' (absorbed + then re-emission).

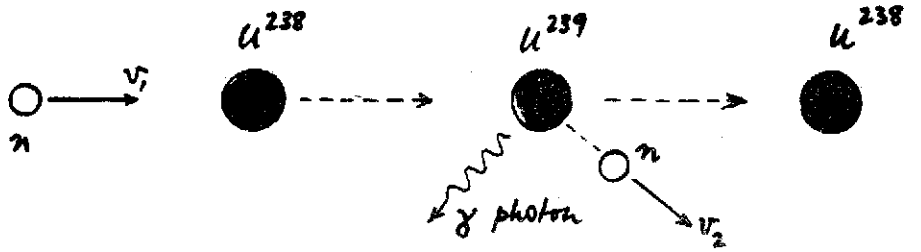

Fig. 2. Inelastic Scattering (n,n¹)

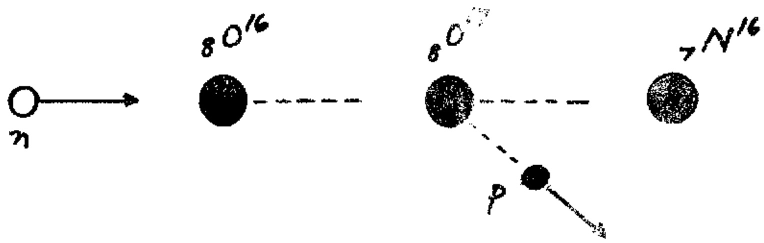

Fig. 3. Transmutation (n,p)

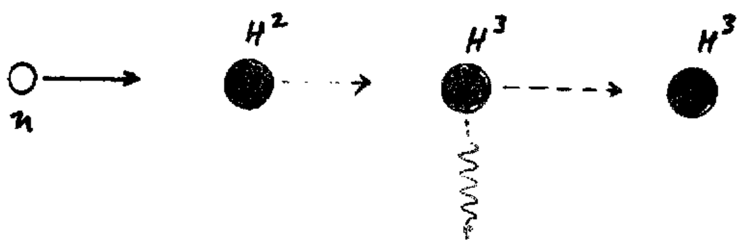

Fig. 4. Radiative Capture (n,γ)

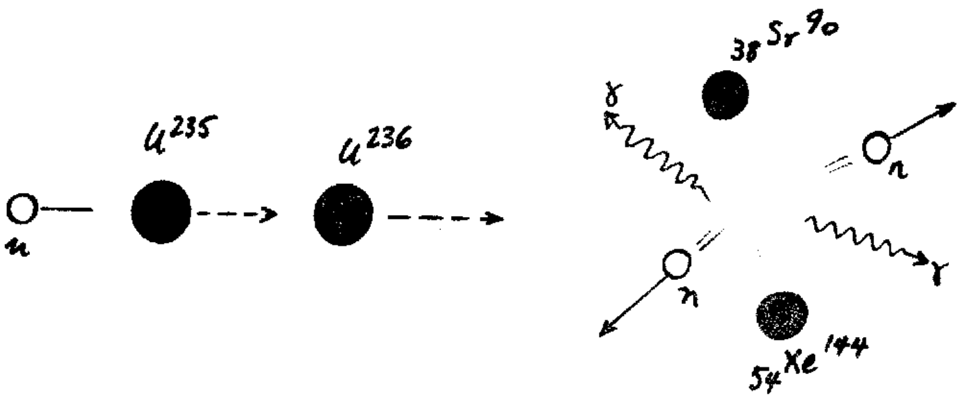

Fig. 5. Fission (n,f)

2. The compound nucleus may emit a charged particle (either a proton or an alpha particle) and so form an entirely new element. Fig. 3 shows such a *transmutation* of oxygen-16, which can occur if the neutron energy is greater than about 10 MeV. This reaction may be written as

$$_0n^1 + {}_8O^{16} \longrightarrow {}_7N^{16} + {}_1p^1$$

or you may prefer the short-hand version $O^{16}(n,p)N^{16}$. The N-16 is radioactive and emits high energy gamma radiation. It represents a radiation hazard in any region where 0-16 (usually in water - H_2O or D_2O) is irradiated with high energy neutrons. The same applies to $O^{17}(n,p)N^{17}$.

There are a number of other (n,p) or (n,α) reactions of interest to us:-

$S^{32}(n,p)P^{32}$:- radiation monitoring film badges often contain a sulphur pellet. After exposure an estimate of the high energy (>2 MeV) neutron dose may be obtained by counting the activity of the phosphorus-32 (a β^- emitter with a 15 day half-life).

$B^{10}(n,\alpha)Li^7$:- reactor instrumentation for monitoring the neutron population utilises this reaction. It is possible at all neutron energies, and releases 2.5 MeV as kinetic energy of the helium and lithium nuclei. This can be detected relatively easily, even in the high gamma background of a reactor environment.

$He^3(n,p)H^3$:- very sensitive reactor instrumentation would make use of this reaction, because it occurs with much greater frequency than the above. He-3 counters were used for the initial start-up of the Pickering reactors.

3. The most common neutron reaction is *radiative capture*, so called because the compound nucleus has *captured* a neutron to *radiate* a gamma photon. Such gamma photons are frequently called *capture gammas*. Radiative capture can occur with practically all nuclei for all neutron energies. Generally speaking, its probability increases as the neutron energy decreases.

An example of such a reaction is shown in Fig. 4, which explains how tritium (hydrogen-3) is produced in heavy water reactors.

Radiative capture is important for two reasons:

(a) Any neutron capture in the reactor materials is undesirable because, simply speaking, it represents a waste of neutrons. The one exception to this is that the $U^{238}(n,\gamma)U^{239}$ reaction ultimately produces plutonium-239, which has desirable fuel properties.

(b) The product nucleus formed more times than not is radioactive and might present a radiation hazard. For example, corrosion products circulated by the heat transport system will be activated as they pass through the reactor core. When they later plate out in this system, the whole system becomes a radioactive hazard, and will remain so even if the reactor is shut down (ie, if the neutron source is removed). The three most troublesome activation products in our reactors are cobalt-60, manganese-56 and copper-64, and they are produced in this way.

4. The final reaction we are going to consider is called *fission.* The word is borrowed from the biologists, who use it to describe the breaking up of a cell into two new ones. In the fission reaction the compound nucleus will usually split into two new nuclei (called *fission fragments*) and an average of two or three new neutrons. Generally speaking, fission reactions are relatively rare; an example is shown in Fig. 5. A detailed explanation of the fission process will be given in the next lesson.

ASSIGNMENT

1. (a) Why are neutrons more effective than charged particles in causing nuclear reactions?

   (b) Why are slow neutrons more likely to cause a nuclear reaction than fast neutrons?

2. Calculate the percentage energy loss of neutrons striking U-238 and H-2 nuclei in head-on and 45^0 collisions.

3. With the help of information given in lesson 127.10-1 explain why the energy required for inelastic scattering of neutrons has to be ~0.1 MeV for uranium, and much more than this for lighter nuclides.

4. What is the distinction between radiative capture and activation? Give examples.

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