

## Chapter 1

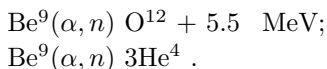
# Sources of Neutrons

### 1.1 Natural Sources

Bombardments of certain elements with natural radiations may result in the production of neutrons. The reaction  $\text{Li}^7(\alpha, n)\text{B}^{10}$  is a possible source of this kind. A certain minimum  $\alpha$ -particle energy is required to initiate the reaction. The masses of the nuclei involved are set out below:

${}_3\text{Li}^7$	7.01804	${}_5\text{B}^{10}$	10.01605
${}_2\text{He}^4$	<u>4.00388</u>	${}_0n^1$	<u>1.00893</u>
	<u>11.02192</u>		<u>11.02498</u>

The total mass of the product nuclei exceeds that of the primary nuclei by 0.00306 mass units, which is equivalent to 2.85 MeV. This is the kinetic energy that must be supplied to the system in the centre of gravity frame in order that the reaction shall take place. The measured energy of the  $\alpha$ -particle in the laboratory frame has to be greater than this by a factor  $\frac{7+4}{7}$ , that is 4.5 MeV approximately. The reaction thus has a threshold at this energy, and the yield rises sharply with increasing  $\alpha$ -particle energy, as indicated in Fig. 1.1. Other reactions of this type are:



The natural neutron sources may be divided into two groups, according to whether the disintegrations are produced by  $\alpha$ -particle or  $\gamma$ -rays.

#### 1.1.1 Alpha Particle Sources

1. Ra-Be. As usually prepared, this consists of a mixture of Be powder and a radium salt. A typical composition would be 5g Be and 1g Ra. This is a

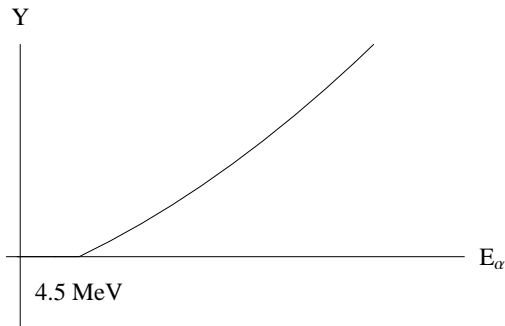


Fig. 1.1

good source, but it must be remembered that it also emits  $\gamma$ -rays.

2. Rn-Be. This takes the form of a vial of Rn gas surrounded by walls of Be. Again there is a certain amount of  $\gamma$ -radiation; there is the additional drawback that the source decays with the half life of radon itself - only 4 days. Both Ra-Be and Rn-Be sources give about  $10 \div 15 \times 10^6$  neutrons/curie/s; the energy spectrum is continuous, with a peak at 1 or 2 MeV and an upper limit of about 13 MeV.

In Fig. 1.2 is shown the radioactive decay series<sup>1</sup> beginning with Ra, with the various  $\alpha$ -particle energies marked. From this diagram it will be possible to infer which  $\alpha$ -particle groups will be effective in any neutron-producing reaction under consideration, once the mass excess or deficiency for the process is known.

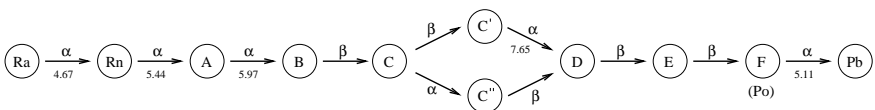


Fig. 1.2

3. Po-Be. There is very little  $\gamma$ -radiation associated with this source, but the neutron intensity is rather low -  $2.8 \times 10^6$  neutrons/curie/s.

<sup>1</sup>@ In this figure, the old notation for radium decay products (A,B,C, etc.) is used; Rn (Radium emanation) corresponds to Rn<sup>222</sup>, Ra A to Po<sup>218</sup>, Ra B to Pb<sup>214</sup>, Ra C to Bi<sup>214</sup>, Ra C' to Po<sup>214</sup>, Ra C'' to Tl<sup>210</sup>, Ra D to Pb<sup>210</sup>, Ra E to Bi<sup>210</sup> and Ra F to Po<sup>210</sup>, respectively.

4. Other sources.

$$\begin{aligned} & \text{B}^{11}(\alpha, n) \text{N}^{14}, & 1.1 \times 10^6 \text{ n/curie/s;} \\ & \text{F}^{19}(\alpha, n) \text{Na}^{22}, & 10^5 \text{ n/curie/s;} \\ & \text{Po-BF}_3 \text{ is a good mock fission source.} \end{aligned}$$

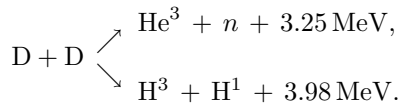
### 1.1.2 Photo-Neutron Sources

1. The reaction  $\text{Be}^9(\gamma, n) \text{Be}^8$  has a threshold at 1.61 MeV. Two of the radium  $\gamma$ -rays are above this energy, giving neutrons of 0.12 MeV and 0.51 MeV respectively.
2.  $\text{D}^2(\gamma, n) \text{H}^1$  has a threshold at 2.17 MeV. Only one of the Ra  $\gamma$ -rays is above this energy, so the source is monochromatic.
3. The  $\gamma$ -rays from  $\text{MsTh}^2$  give neutrons of 0.220 MeV from  $\text{D}_2\text{O}$ , and two groups of 0.82 and 0.16 MeV, from Be.
4. Using  $\gamma$ -ray sources prepared in the Argonne pile, the following neutron sources have been made:

$\gamma$ -ray emitter	Target	Neutron energy
Sb	Be	0.030 MeV
Ga	$\text{D}_2\text{O}$	0.12
Na	$\text{D}_2\text{O}$	0.24
La	Be	0.62
Na	Be	0.82

## 1.2 Artificial Sources

Probably the best known artificial source is the D-D reaction:



The yields of the alternative branches of the reaction are approximately equal. The neutron yield per incident deuteron from a thick  $\text{D}_2\text{O}$  (heavy

<sup>2</sup>@ Mesothorium denotes generically the first two decay products of thorium, that is  $\text{Ra}^{228}$  (mesothorium I) and  $\text{Ac}^{228}$  (mesothorium II).

ice) target is given below for various deuteron energies:

$E_D(\text{keV})$	0	50	100	200	300	500	1000	2000
Yield $\times 10^7$	0	0.2	0.75	3.0	7.0	22	120	700

The reaction  $\text{Li}^7(p, n) \text{Be}^7$  is useful in that it can be used to produce mono-energetic neutrons over a large range of energies (about 50 keV to several MeV). It is an endo-ergic<sup>3</sup> reaction, with a Q value of -1.62 MeV, and hence a threshold of  $\frac{8}{7} \cdot 1.62 = 1.86$  MeV.

Another commonly used reaction, usually employed as a source for a cyclotron, is the process  $\text{Be}^9(d, n) \text{B}^{10}$ . The thick target yields at 1 MeV and 8 MeV incident deuteron energy are about  $10^8$  and  $10^{10}$  neutrons/s/ $\mu\text{A}$ , respectively.

There are many other light particle reactions with good yields, but most of them give rise to complex neutron spectra.

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<sup>3</sup>@ Here and in the following, the author uses this compact form for endo-energetic.