Neutrons:

- Neutrons were discovered by Chadwick in 1932 but they were postulated before for a number of reasons:

  -- Rutherford had proven that nuclei and protons exist and the existence of isotopes had been proven by him and Mme. Curie. In particular, Rutherford transmuted $^{14}\text{N}(\alpha,p)^{17}\text{O}$.

  -- In the 1920's, Rutherford argued that "symmetry" required the existence of a neutrally charged particle with a mass similar to a proton.

  -- Mme. Curie-Joliet showed that radiation from Be-9 bombarded with alphas had a penetrating power greater than gamma rays and noted that this radiation could produce protons and other light nuclei but she thought that the radiation was electromagnetic. Others thought it was Rutherford's neutral particle.

- Chadwick's 1932 experiment was simple and elegant. He put paraffin wax between the radiation produced by the bombardment of Be-9 by alpha particles $^9\text{Be}(\alpha,n)^{12}\text{C}$ and an ion chamber and showed that there was a significant increase in the ion current.

- Instead of Be-9, can use Deuterium from another source, i.e., Detroit fast neutron fac.
• By placing Al absorbers in front of the ion chamber, the range of the recoil protons (and thus energy) was measured. Other light elements and their ranges were measured as well. The best explanation was a neutral beam of particles with the mass about the same as the proton. Chadwick's estimate of the mass of the neutron was 1.006 times the mass of the proton close to the modern value.

• Neutron Interactions with Matter

• We now know that neutrons interact only by the strong (or nuclear) force and so they only interact with nuclei and are ideal probes for nuclei.

• Elastic scattering: X(n,n)X

  -- The neutron scatters off of a nucleus, transferring energy and momentum to the nucleus but the system of the nucleus and neutron have the same energy before and after the interaction.

  -- The recoil energy of the nucleus is given by:

  \[ T_x = T_n \left( \frac{4M_nM_x}{(M_n + M_x)^2} \right) \cos^2 \varphi \]

  -- If the nucleus is a proton, since the proton and neutron have nearly the same mass, then on average the proton and neutron will share the kinetic energy \( \langle T_p \rangle = \langle T_n \rangle = 1/2 \), but on any given interaction, the particle that goes more in the forward direction will get more energy. If the proton goes directly in the forward direction it will get all of the energy and the neutron will be at rest. This is why hydrogen rich materials are used in neutron shielding.

  -- Elastic scattering proceeds until the neutron is in thermal equilibrium with its environment, when then it is said to be a thermal neutron. The average energy of a thermal neutron is 0.025 eV and its distribution corresponds to a Maxwellian energy distribution as if it were a gas:

  \[ f(E) dE = \frac{2mE^{1/2}}{(\pi kT)^{3/2}} e^{-E/kT} dE \]
Where,

-- E is the kinetic energy, T is temperature in Kelvin, and n is the number of neutrons per unit volume.

![Graph](image.png)

**Figure 12.4** Maxwellian energy distribution, a representation of the neutron energy spectrum after many scatterings.

(From Krane, Introductory Nuclear Physics)

- **Inelastic scattering** $X(n,n)X^*$ (some excitation, often released by a gamma ray)
  
  -- In inelastic scattering the product nucleus is left in an excited state so the kinetic energy before and after the interaction are not the same. The nucleus de-excites often with the emission of a gamma-ray.

- **Non-elastic reactions**: (nuclear reactions)
  
  -- In non-elastic reactions, the product is transmuted from its parent. These reactions have revealed much about the nucleus.
  
  -- There are many possibilities for fast neutrons, e.g., $X(n,p)$, $X(n,\alpha)$, $X(n,2n)$, $X(n,2\alpha)$,... and resonance features reveal nuclear shell structures including spin states.
  
  -- Neutrons can produce particles of well defined energies. For example,

  $$^{27}Al(n,p_n)^{27}Mg$$

  Where,

  -- $p_n$ refer to protons with a well defined energy labeled by n, correspond to bound final states in the product nucleus.
The In cross-section, from Krane:

For slow or thermal neutrons, the reactions are called capture reactions. Fermi observed that when neutrons are slowed down their interaction cross-section is very large and varied approximately inversely with their velocity. This $1/v$ dependence suggests that the capture is directly proportional to the time the neutron spends close to the nucleus.

Also from Krane, cross-section for capture:

Some nuclei such as B-10 strongly absorb thermal neutrons.
• **Neutron Sources:**

• α-Be source:

  -- This laboratory source was used in the discovery of the neutron. $^9$Be has a relatively loosely bound neutron (1.7 MeV binding energy). An alpha particle from a naturally occurring radioisotope have typical energies of 5-6 MeV, a neutron can be released with a $\Sigma Q$ of 5.7 MeV with the most probable energy of the neutron of about 5 MeV. The trouble with this source is that the alpha emitting natural sources produce substantial gamma rays.

• Photoneutron sources:

  -- This process is the same as discussed in a lecture on photon interaction. This source produces more monoenergetic neutrons than other neutron sources if the photon source is monoenergetic (e.g., $^{24}$Na has a strong gamma line at 2.76 MeV but this photon source only has a 15 hr half-life)

• Spontaneous fission:

  -- A few radioisotopes produce neutrons. The most important is Cf-252 which has a 2.65 yr half-life. Spontaneous fission occurs in about 3% of the decays and competes with alpha decay. Each fission event creates 4 neutrons so the neutron production rate is about $2.3 \times 10^{12}$ neutrons/s. The neutron spectrum so produced is broad with an average energy of about 2 MeV.

• Reactor sources:

  -- The only source to get high neutron fluence rates and useful for the production of radioisotopes by neutron capture.

  -- The energy spectrum extends to 5 - 7 MeV but peaks at about 1 - 2 MeV.

• Nuclear reactions:

  -- These sources employ an accelerator to produce a beam of particles.

  -- At a selected angle from the beam path, the neutron energy will be close to monoenergetic.

  -- An example reaction is the typical highest cross-section fusion reaction: D-T gives a 14MeV neutron:

    $$^3\text{H} + d \rightarrow ^4\text{He} + n \quad \Sigma Q= +17.6 \text{ MeV}$$
• **Neutron Interaction in Tissue:**

• The multiple interaction mechanisms and complex dependence on isotope means that there will be a strong tissue type dependency.

• Recall that when there is electronic equilibrium there is an equality between dose and collision Kerma. Since the mass of the charged particles set in motion by neutrons in tissue such as protons and alpha particles is so high, there is negligible difference between collision Kerma and Kerma. Therefore, when there is electronic equilibrium, the neutron dose is equal to Kerma. Recall that Kerma is equal to the product of the mass energy transfer coefficient and the energy fluence:

\[
D = K = \frac{\mu_{iz} \Phi}{\rho} = \frac{\mu_{iz} E}{\rho} \Phi
\]

Where,

-- E is the kinetic energy of the neutron: not captured

• Since there is such a strong energy dependence and a large variety of interaction types and isotopes, instead of tabulating a long list of isotopes for tissue, the ratio of Kerma to fluence is tabulated and this is equivalent to the product of mass energy transfer coefficient and mean neutron energy. Another reason is the ambiguity of the energy term E in the energy fluence. When the neutron is captured, one uses the total energy and when it is not, the kinetic energy is used. Tabulating the ratio of Kerma to fluence eliminates this ambiguity. The ratio of Kerma to fluence is called the neutron Kerma factor.
- Neutron Kerma factors for tissue are graphed below, from Attix:

**CONTRIBUTIONS TO KERMA**

<table>
<thead>
<tr>
<th>CURVE</th>
<th>REACTION</th>
<th>PARTICLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>ALL</td>
<td>TOTAL KERMA</td>
</tr>
<tr>
<td>b.</td>
<td>HYDROGEN ELASTIC</td>
<td>PROTONS</td>
</tr>
<tr>
<td>c.</td>
<td>ELASTIC</td>
<td>OXYGEN IONS</td>
</tr>
<tr>
<td>d.</td>
<td>ELASTIC</td>
<td>CARBON IONS</td>
</tr>
<tr>
<td>e.</td>
<td>ELASTIC</td>
<td>NITROGEN IONS</td>
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<tr>
<td>f.</td>
<td>ALL NON ELASTIC IONS HAVING MASSES</td>
<td>2-16 EXCEPT a</td>
</tr>
<tr>
<td>g.</td>
<td>ALL (n,p) REACTIONS</td>
<td>PROTONS</td>
</tr>
<tr>
<td>h.</td>
<td>ALL (n,a) REACTIONS</td>
<td>ALPHAS</td>
</tr>
</tbody>
</table>

- Notice the dominance of recoil protons!

**FIGURE 16.1.** Kerma per unit fluence contributed by various interactions in a small mass of tissue in free space, as a function of incident neutron energy. Note that curves $g$ and $h$ are displaced downward by the factor $10^{-3}$. (Auxier et al., 1968. Reproduced with permission from J. A. Auxier and Academic Press.)
• **Neutron Detectors:**

  Neutrons, being neutral particles, are indirectly ionizing radiation.

  Most neutron detectors have modified cavity or wall materials that rely on nuclear reactions to convert neutrons to charged particles.

  For slow and thermal neutrons, detectors based on \((n,p)\) and \((n,\alpha)\) are favored.

  An example is \(^{10}\text{B} + n \rightarrow ^7\text{Li}^* + \alpha\) where \(^7\text{Li}\) is left in an excited state with an energy of 0.48 MeV. For thermal neutrons the cross-section is about 3840 barns and follows the \(1/v\) law as the energy increases up to about 100 keV.

  A detector system unique to neutron detection is activation of foils.

  There is some confounding influence of gamma rays above about 10 MeV due to the photonuclear interaction, however, at lower energies only neutrons can activate the foils.

  Generally, a variety of metals are used so that there is some ability to determine the energy of the neutrons.

  The foils are placed in the neutron beam and transmutation produces a radioactive isotope. The activity of the product builds up and reaches equilibrium where the decay of the product is equal to the activation of the product.

  The radioactivity of the foils are counted and the neutron fluence rate can be determined knowing how long the foil was activated and the time after removal from the beam.

  A variant of foil activation are fission foils. The foils are fissionable material but need not be material that can be used for weapons (i.e., fissile material). Isotopes such as \(^{237}\text{NP}, ^{238}\text{U}\) and \(^{232}\text{Th}\) are used.

• **Neutron Source Calibration:**

  In the US, NIST has a neutron source calibration facility that uses a manganous sulfate (MnSO\(_4\)) bath. This method can determine neutron source strength for emission rates between \(5 \times 10^5\) to \(1 \times 10^{10}\). The method relies on the capture of a neutron: \(^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}\). The gammas are detected with NaI(Tl) detectors. At NIST, a Ra-Be photoneutron source is used as the standard. In Korea at KRISS, a standard of Cf-252 is used.
• The source is placed at the center of a spherical bath, like this one at KRISS:


• The following equation is used for the source strength calculation:

\[ Q = \frac{A}{\varepsilon \cdot L \cdot (1-O)(1-S)} \]  
with units of \([Q] = [A] =\text{cps} = \text{neutrons/s} \]

Where,

-- \(A\) is the Mn-56 activity in the bath.
-- \(\varepsilon\) is the NaI(Ti) detector efficiency.
-- \(L\) is the neutron bath leakage loss.
-- \(O\) is the fast neutron absorption loss in Oxygen and Sulfur.
-- \(S\) is the self-absorption loss in the source structure.
-- \(f\) is the fraction of neutron absorbed in Mn-55

* The end of the course !!!!