CHAPTER III

PROPERTIES OF NUCLEONIC COMPONENTS

3:1 SHOWERS PRODUCED BY HIGH ENERGY PARTICLES

The term shower is used to identify the chain of events that is initiated by the cosmic ray particles of ultra-high energy interacting with any nuclei. The products of the interaction, moving practically in the same direction as the primary cosmic ray, give rise to a cascade of the other interactions, until in the end, a number of secondaries is created which can be as high as many millions.

According to the present knowledge, there are two kinds of showers;

1. air showers,
2. penetrating showers.

3:1:1 Air showers

Air showers are produced by those rare primary cosmic ray particles whose energy is much greater than that generated by the most powerful particle accelerators. The minimum energy necessary to produce a shower observable at sea level is about 10^{14} ev. The energy of the particles responsible for the largest shower ever observed is about 6×10^{19} ev (20). The primary cosmic ray of ultra-high energy interacting with air nuclei in the upper atmosphere, gives rise to a cascade of other interactions. On reaching the lower atmosphere a large number of secondaries is produced.

Those secondaries all arrive at practically the same time on a plane perpendicular to the direction of the original particles, during their tranversal of a kilometer of air and are scattered around the axis up to a distance of several hundred meters. The shower thus covers a circular area of many thousands of square meters with maximum density in the central region (the "core" of shower).

3:1:2 Penetrating showers

Penetrating showers are produced by ultra-high energy particles while penetrating through any dense and heavy nuclei materials. On interacting with the heavy nuclei, the ultra-high energy particles give rise to secondaries. The ultra-high energy particles consist of nucleons, π-mesons, and muons. The nucleon-nucleon and muon-nucleon cascades display distributions similar to those of the photon-electron cascades.

The penetrating showers for instance, the "explosive showers", which were detected in early work with multiple plate cloud chambers by Fussell (23) and Powell (24), and underground cloud chamber studies by Braddick and Hensby (25) gave additional proof for the existance of such showers.

3:2 NEUTRONS PRODUCED BY HIGH ENERGY PARTICLES

The primary particles interact with air nuclei to yield secondary high energy mesons, nucleons and fragments. These secondary particles generated by collision processes in the atmosphere are a cascade or chain composed principally of nucleons. As the cascade degenerates in total energy, the composition of the cascade becomes almost entirely nucleons of less than 1 Gev/c. The degradation of nucleons energy continues through collision and capture processes which are recognized as nuclear disintegrations or "stars" (See Fig. 3.1). At atmospheric depths sufficient for the nucleon flux and star production to be in equilibrium ($X > 200$ gm-cm^{-2}). Each nucleon disintegration yields on the average several protons and neutrons having energies in the range 1 to 20 Mev. These low energy nucleons are called disintegration product nucleons. The protons rapidly lose energy by ionization, and the neutrons are reduced in energy by nitrogen and oxygen collisions to become the slow neutrons in the atmosphere (26),

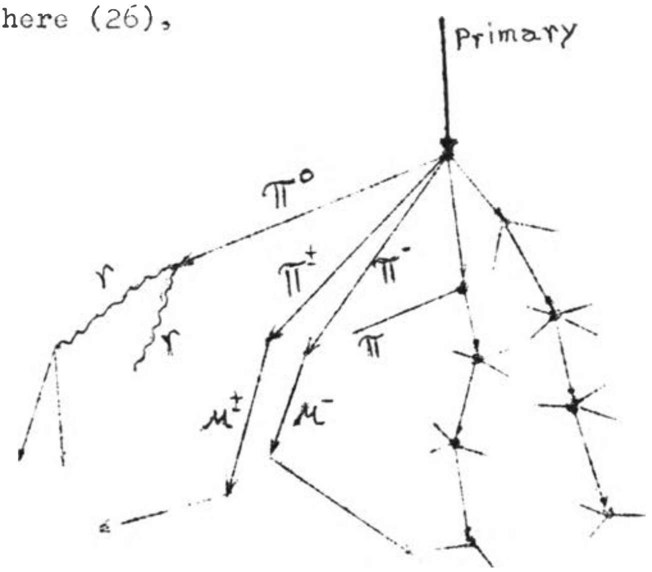

Fig. 3.1 Nuclear disintegration processes

The production of neutrons by nuclear disintegration process or "star" occurs not only in the atmosphere but also in condensed materials (11). We define this process as "local neutron production", and the neutron production in elements is a function of atomic weight, see Fig. 3.2. These nuclear disintegrations are locally produced by μ-meson, π -meson and nucleons, eg. protons and neutrons.

The disintegration product neutron will cause nuclear events if its energy is in the kiloelectronvolts (Kev) range. If the energy decreases to about 1 ev, it will be absorbed by N^{14} thus:

$$N^{14} + n = C^{14} + p.$$

However, most of the neutrons may not attain energies low enough to cause the reactions with nitrogen nuclei, since they decay to proton and electron and antineutrino with the mean life of 770 seconds as in the equation below,

$$n \dashrightarrow p + e^{-} + \bar{\nu} .$$

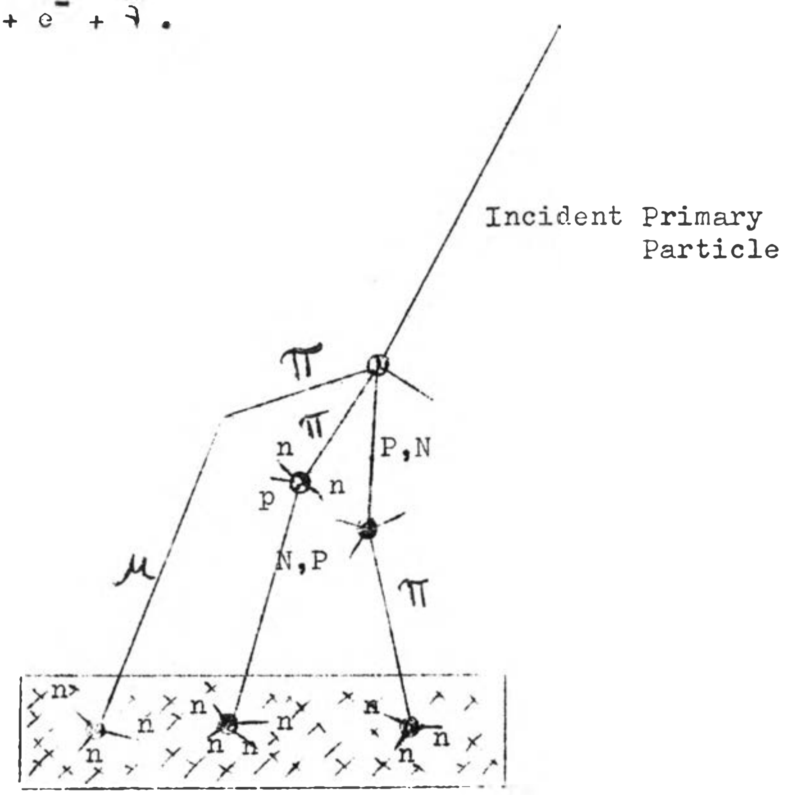

Fig. 3.2 Local neutron production

3:3 NEUTRON MULTIPLICITY

The multiplicity of the production of neutrons in lead was first studied by G. Cocconi, V. Cocconi Tongiorgi, and M. Widgoff (7,27,28,29). In 1950 Cocconi et al, measured neutron multiplicities for mountain altitude (30). The result of the measurement was that the multiplicities are 50 for a 4.5 inch Pb producer, but only 10 for a 0.25 inch Pb producer. And in 1954 W.C.G. Ortel (31) found that the result of this measurement fairly agrees with the previous ones.

B.F. Sterns in 1957 (32), at Washington University, by using the magnetic spectrograph found the average multiplicity for neutrons released in nuclear disintigration from a 2 inch Pb producer to be from 30 to 60.

In 1962 some statistical studies of the multiplicity factor were made by Dyring; the experiments which actually included a standard monitor as a neutron source were performed by Hughes et al (33), and the magnetic spectrograph experiment was performed by Meyer (33). They found the relation of the multiplicity to the incident particle energies and also found the protons' momentum in these events between 0.3 and 150 Gev/c. Fig. 3.3 (33) and 3.4 (34) show the relation between the multiplicity and the impact particle energy.

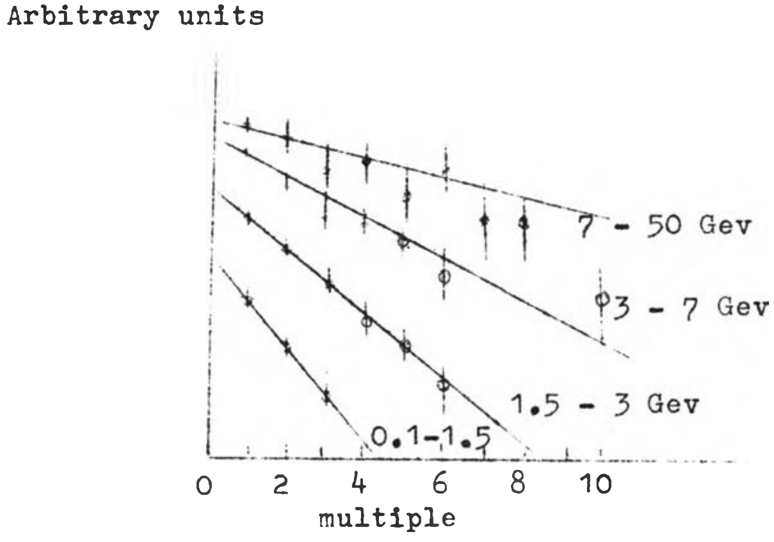

Fig. 3.3 The Frequency of Multiple Neutron Production in Lead for Four Momentum Regions.

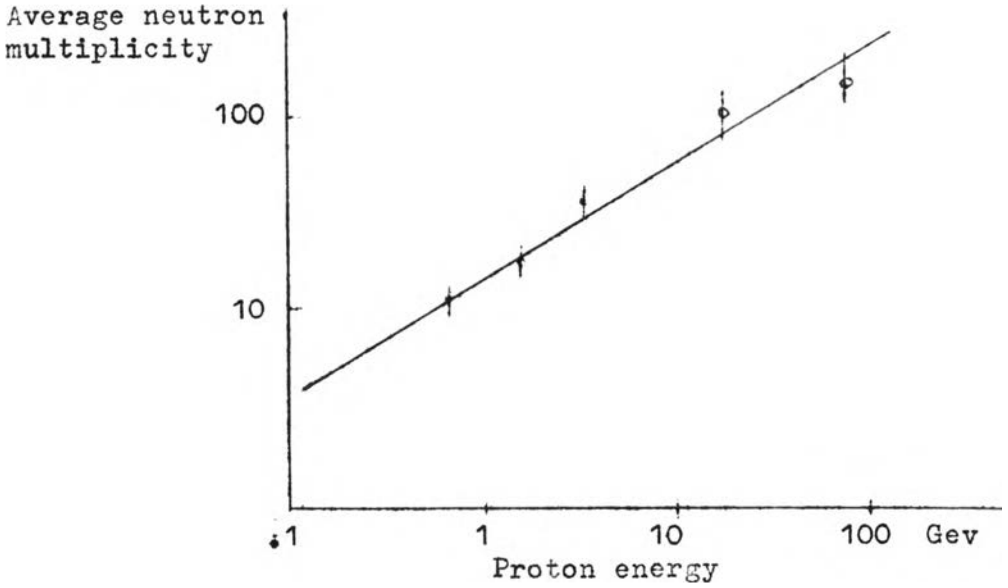

Fig. 3.4 Average Neutron Multiplicity According to the Experiment Results of Hughes et al (1962).

However, the multiplicity factor of standard neutron monitors has been found to be 1.1 to 1.3 (35). It is apparently an individual feature of the monitor. This is understandable as it certainly is a function of the proton spectrum at the lead core. It is also a function of the probability of the neutrons being brought into the thermal energy range and the time delays due to this process. In this way even details of the geometry become important. (They will be discussed in chapter IV.)

3:4 SLOWING-DOWN OF NEUTRONS

The neutrons can be devided into somewhat arbitrary energy groups as follows: neutrons above 100 Kev are called fast neutrons, those in the 100 ev to 100 Kev energy bracket, intermediate, those about 0.025 ev to 100 ev, slow neutrons, while neutrons of about 0.025 ev energy are known as thermal neutrons. If we neglect the nuclear reactions, then we can consider the slowing down process of the fast neutrons as a biliard-ball collision problem.

Fermi and his colleagues (1934) showed that the neutrons are slowed down in hydrogenous materials, apparently without being absorbed, and the slower neutrons have a greater probability of inducing radioactivity than more energetic neutrons. The conversion of fast neutrons into slow neutrons has been investigated in great detail both experimentally and theoretically, and the importance of slow neutrons and the slowing down process has been demonstrated beyond question. A complete and rigorous treatment of neutron slowing down involves complicated mathematics, but the underlying principles and some of the most useful result are quite simple and can be illustrated with little difficulty. For most practical purposes, the important slowing down process is elastic scattering by light nuclei. Inelastic scattering by intermediate or heavy nuclei is important for neutrons with energies above 1 Mev, but becomes practically negligible below this energy. For simplicity, therefore only elastic scattering by light nuclei will be considered.

The amount of energy that a neutron loses in a simple collision can be calculated by solving the equations of conservation of energy and momentum for the energy of the neutron after the collision. The average energy loss per collision can be calculated by the equation;

$$\frac{E}{E_0} = \frac{A^2 + 1 + 2A \cos \Phi}{(A + 1)^2}$$

$$= \frac{1 + r}{2} + \frac{1 - r}{2} \cos \Phi ,$$

where E_0 is the initial energy of neutron,

E is the final energy of neutron after collision,

$A = M/m$ is the ratio of moderator mass to neutron mass,

and Φ = Angle between initial and final direction of neutron.

$r = \left(\frac{(A - 1)}{(A + 1)}\right)^2$ is the energy ratio.

For convenience in neutron energy slowing down calculations, a quantity ξ was introduced; it is the average decrease per collision in the logarithm of the neutron energy.

Then $$\xi = 1 + \frac{r}{1 - r} \ln r$$

$$= 1 - \frac{(A - 1)^2}{2A} \ln \frac{(A + 1)}{(A - 1)}$$

The mass ratio A can be taken equal to the mass number of the moderator without introducing any significant error, since m is close to unity and M is very close to an integer.

For example, in a collision with a target nucleon with A = 200, a neutron can lose, in an elastic collision not more than 2 per cent. This energy loss is very small compared with the possible loss of 28 per cent in a collision with a carbon nucleus, A = 12, and shows that heavy nuclei are poor moderators.

The formulas for ξ, break down for two special cases, A = 1 (hydrogen) and $A = \infty$, because the functions on the right sides of the equation are no longer determinate. By taking the appropriate limits as $A \longrightarrow 1$ or as $A \longrightarrow \infty$, values of ξ can be obtained. For A = 1 (hydrogen), $\xi = 1$, which means that the neutron energy decreases on the average by the factor e = 2.72; the energy after a collision is only 37 per cent of its original energy. It can also be seen that in a head -on collision between a neutron and proton, which have nearly equal masses, the former can lose all of its energy. This possibility distinguishes by hydrogen from other moderators.

For $A \longrightarrow \infty$, $\xi \longrightarrow 0$, so that a neutron loses practically no energy in an elastic collision with a heavy nucleus, as found above.

When ξ is known, the average number of collisions needed to bring about a given decrease in neutron energy can easily be calculated. For example if the neutrons start out with an average energy of 2 Mev, and if they are to be slowed down to 0.025 ev (thermal energy at ordinary room temperature), the total logarithmic energy loss is

$$\ln (2 \times 10^6 / 0.025).$$

Since the average loss per collision is ξ, then the number of collision is given by,

$$\text{average number of collision (2 Mev to 0.025 ev)} = \frac{\ln\left(\frac{2 \times 10^6}{0.025}\right)}{\xi} = \frac{18.2}{\xi}$$

The value of ξ and of the average number of elastic collision needed to reduce the neutron energy from 2 Mev to 0.025 ev are listed in table 3.1 for several nuclear species.

Table 3.1 Scattering Properties of Some Nuclei

Element	A	ξ	Number of collision from 2 Mev to 0.025 ev.
Hydrogen	1	1.000	18
Deuterium	2	0.725	25
Helium	4	0.425	43
Lithium	7	0.267	67
Beryllium	9	0.208	87
Carbon	12	0.158	114
Oxygen	16	0.120	150
Uranium	238	0.0084	2150

3:5 NEUTRON DETECTION

Neutrons are uncharged particles and produce a negligible amount of ionization in passing through matter, with the result that they cannot be detected directly in any instrument (Geiger counter, cloud chamber) whose action depends on the ionization caused by the particle which enters it. The detection of neutrons depends on secondary effects which result from their interactions with nuclei (36). Some of the reactions are as follows:

1. The absorption of a neutron by a nucleus with the prompt emission of a fast charged particle: examples are (n,α), (n,p), (n,γ), and (n, fission) reactions. The alpha particle, the proton, the gamma ray or the fission products give instantaneous imformation concerning the neutron.

2. The absorption of a neutron with the formation of a radioactive nuclide whose activity can be measured. This method is based on the fact that many nuclear reactions induced by neutrons result in radioactive product nuclei, and the neutrons are detected by means of the activity of an exposed substance.

3. Elastic scattering of neutrons in which the recoil particle is charged and is capable of being detected. The most important example of this process is the elastic scattering of a neutron by a proton; the

latter particle can be imparted up to 100 per cent of the neutron energy.

A neutron detector based on the first type of interaction can be an ionization chamber or a proportional counter. One of the most frequently used detectors is based on the reaction B^{10} (n,α) Li^{7}, which is exoergic, with an energy release of Q = 2.78 Mev. The target nucleus B^{10} which has an abundance of 18.8 per cent in natural boron, is responsible for the high cross section (750 barns) of the latter for thermal neutrons. A chamber or counter can be filled with BF_3 gas or lined with a compound of boron. The gas detector is used more extensively. When high sensitivity is needed, natural BF_3 is replaced by $B^{10}F_3$ made from the separated isotope B^{10}. The cross section for the (n,α) reaction follows the 1/v law and falls off with increasing neutron energy. The sensitivity of BF_3 counters consequently decreases with increasing neutron energy, and these counters are most useful for thermal neutrons.

3:6 NEUTRON MONITOR

To measure the cosmic ray intensity-time variation, it is necessary to have an apparatus which deals effectively with the phenomena mentioned above. Such an apparatus is called Neutron Monitor. The mechanism of the neutron monitor, as shown in Fig. 3.5, will be described in detail in chapter IV.

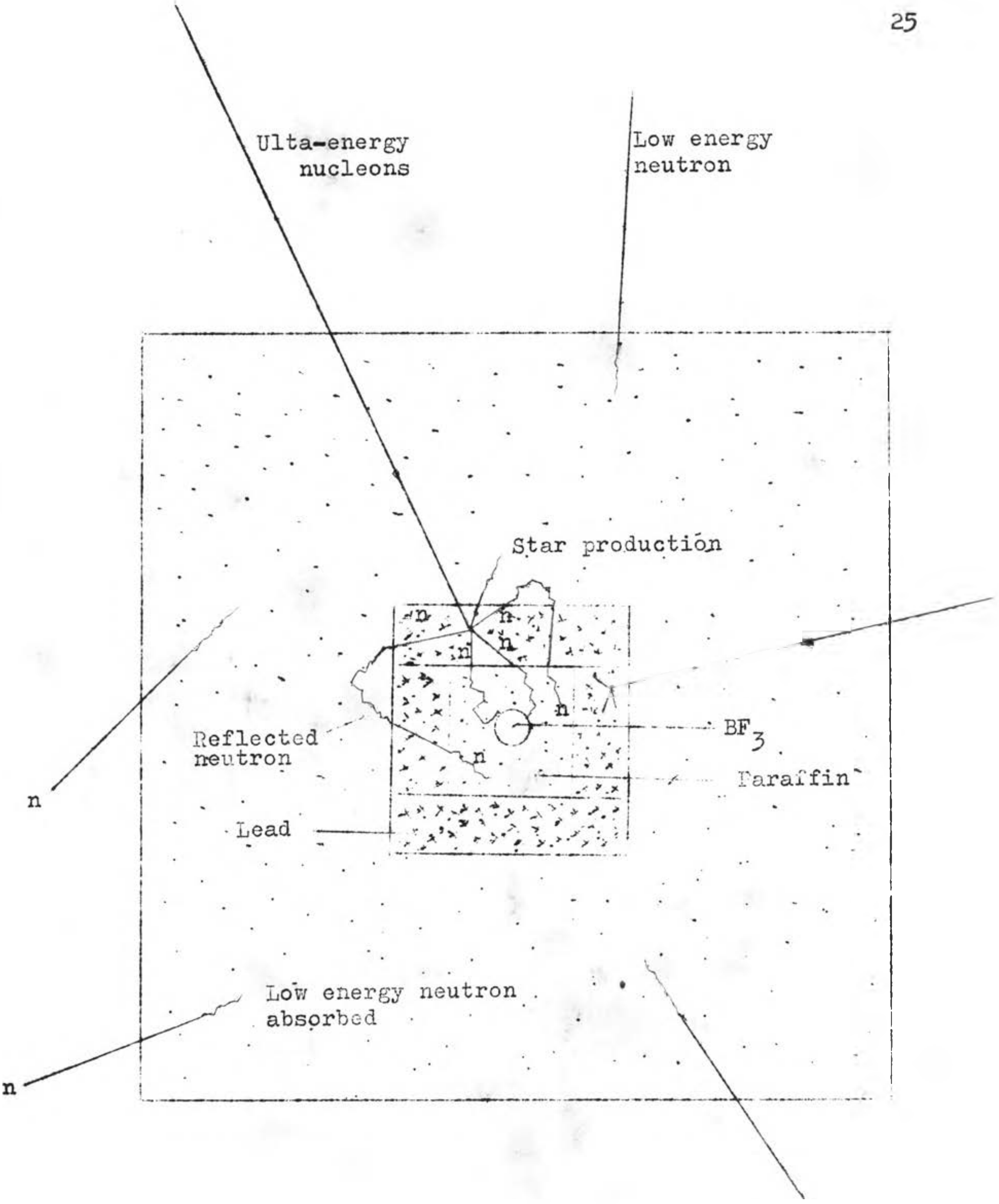

Fig. 3.5 The mechanism of the neutron monitor.