CHAPTER XII

LEAD ABSORPTION OF COSMIC RAY PARTICLES

XII.1 General Remarks.

The interpretation of absorption measurements of cosmic rays in condensed matter is difficult because of the complexity of the phenomena involved and is often complicated further by instrumental factors. The absorption of cosmic rays in lead was observed by Hoffmann(17), Steinke(18), Myssowsky and Tuwim(19) and later by many others. They suggested that the intensity is reduced by about 30 per cent in the first 10 cm of lead. Woodward and Stevenson(20) found that the absorption is more nearly proportional to the electron density than to the mass density. The absorption of hard component is directly proportional to mass of the absorber. The soft component was found by Rossi and Alocco(21) to be absorbed more strongly in heavy elements than in light elements.

XII.2 Absorption Coefficient and Absorption Thickness.

All particles capable of causing nuclear events are called the N-components (N for nuclear) . The N-components decrease exponentially with atmospheric depth according to the relation

$$I = I_0 \exp(-h/L)$$

where I is the intensity of N-components, h the depth from the top of the atmosphere expressed in gm cm^{-2}, and R, the range of the N-components in air, is of the order of [illegible] gm cm^{-2}, **according to George and Jason(22).**

The intensity of the N-rays is found to vary exponentially with the thickness of the absorber, the fraction passing through the thickness X is equal to exp(−aX), where a is the absorption coefficient. The absorption equation may be written as,

$$N = N_0 \exp(-aX)$$

which a is approximately equal to 3 x 10^{-3} cm^2 per gm in lead. The reciprocal value of a is L, the absorption thickness. Measurement of George and Jason(22) gave an absorption thickness of 320 ± 20 gm cm^{-2} in lead, for the star producing radiation.

III.3 The Mean Free Path of the N-Rays.

The mean free path may be expressed

$$\lambda = \frac{\int_0^\infty x\,P(x)\,dx}{\int_0^\infty P(x)\,dx}$$

where P(x) is the probability that the incident particles have no collisions with the target nuclei when pass through the distance x.

The collision mean free path L_c, represents the mean thickness traversed by the particles before undergoing nuclear interactions and may be expressed as

$$L_c = \frac{1}{n\sigma}$$

where n is the number of target particles per unit volume, σ is the effective cross section area for collision. George and Jason(23) have obtained the collision mean free path;

$$\text{in lead } L_c = 300 \pm 40 \text{ gm cm}^{-2}$$

$$\text{in aluminium } L_c = 85 \pm 15 \text{ gm cm}^{-2}$$

The experiments at high altitude of Sitte(24) showed that the mean free path of N-rays decreases with energy. The collision mean free paths of non-ionising N-rays in lead are not significantly different from that of ionising N-rays in the same element.

III.4 The Mean Free Path in Nuclear Matter.

The mean free path in nuclear matter L_n is defined as

$$L_n = \frac{1}{\rho\sigma_n}$$

where ρ is the number of nucleons per cm^3 and σ_n is the cross section. The volume of the nucleus may be calculated from the general formula,

$$V_n = \frac{4}{3}\pi R^3$$

where R is the nuclear radius. The nuclear radius R may be expressed as

$$R = r_0 A^{1/3}$$

The constant r_0 is approximately equal to 1.5×10^{-13} cm. The number of proton per cm^3 is

$$\rho_p = \frac{Z}{\frac{4}{3}\pi R^3}$$

The number of neutron per cm^3 is

$$\rho_n = \frac{A - Z}{\frac{4}{3}\pi R^3}$$

Therefore, the value of the mean free path is dependent of the nuclear radius. The reciprocal of the mean free path, K, the **attenuation coefficient** or the absorption coefficient for a proton inside the nucleus is

$$K_p = \frac{1}{L_{m,p}} = \rho_n \sigma_{np} + \rho_p \sigma_{pp}$$

and for the neutron inside the nucleus is

$$K_n = \frac{1}{L_{m,n}} = \rho_n \sigma_{nn} + \rho_p \sigma_{np}$$

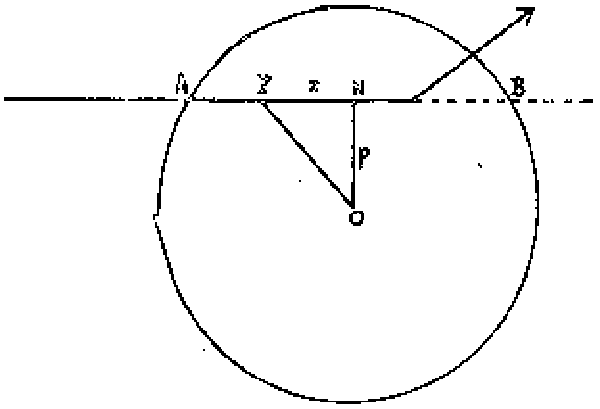
According to S.Flugge(23) the corrected value for the mean free path in the nucleus must be corrected by the Pauli exclusion principle and the cross section may be expressed

$$\sigma_{\rm eff} = \sigma_{\rm free}\left[1 - \frac{7}{5}\frac{P_F^2}{P_1^2}\right]$$

where P_F is the maximum momentum of the Fermi gas and $(P_F^2)/2M$ is nearly equal to 20 MeV. P_1 is the momentum of the incident nucleon, the equation is limited to $P_1 > \sqrt{2}\,P_F$.

III.5 Absorption Cross Section.

Consider an incident beam of particles which enter the nucleus and is attenuated exponentially with an absorption coefficient $K = \rho\sigma_m$. An incident particle travels straightly into the nucleus, being scattered once by the target nucleon and then go out off the nucleus in a straight line.



The impact parameter of the path is p, the coordinates of the particle are(p,z) . By using the method of Elton(10) the total attenuation is obtained by integrating over the length possible path AB, so that the probability of interaction along the path is

$$1 - e^{-S(p)}\ ,\ \text{where}\ S(p)=\int_A^B \rho\left[\sqrt{(p^2+s^2)}\right]\sigma_s ds$$

The total absorption cross section is obtained by integrating the probability over the whole nucleus volume.

$$\sigma_{abs} = \int_0^\infty \left[1 - \exp\left\{ -\int_{-\infty}^{\infty}\rho\left[\sqrt{p^2+s^2}\right]\sigma_s ds\right\}\right] 2\pi p dp$$

From the experiment of Hilton([illegible]) we have known that the neutron and proton distribution is scaled [illegible] the [illegible]. The absorption cross section for [illegible] are shown in Table [illegible], as follows;

Particle	Energy (MeV)	in barns
neutron	95	1.257
	14	1.947
	105	1.975
	140	1.9[illegible]
	300	2.780
	1000	1.950
proton	330	1.960
	870	1.970
	[illegible]	1.609
cosmic ray neutron & proton	30000	2.350
deuteron	190	3.0[illegible]

III.6 Absorption of Various Cosmic Ray Components.

a. Hard and Soft Component The soft component which is absorbed by about 10 cm of lead consists mainly of electron, positron and photons. The hard component is made up primarily of mu-mesons. The absorption curve of the components at the sea level was shown by [illegible](30). (See Fig. III).The momentum of the components passing through lead was tabulated by Rossi(5) as shown,

Particle	Rest Energy(approx)	Momentum to Penetrate 167 gm/cm² Pb, (≥ 10?)	Momentum to Penetrate 5 gm/cm² Brass, (≥ 5)
proton	1.0 BeV	2 BeV/c	0.4 BeV/c
mu-meson	0.1 BeV	0.3BeV/c	0.08 BeV/c
electron& positron	0.5 MeV	10.0BeV/c	10.0 MeV/c

Street(29) and co-workers at Harvard had obtained the absorption curve of total cosmic rays by using cosmic ray telescope. (See Fig.IV)

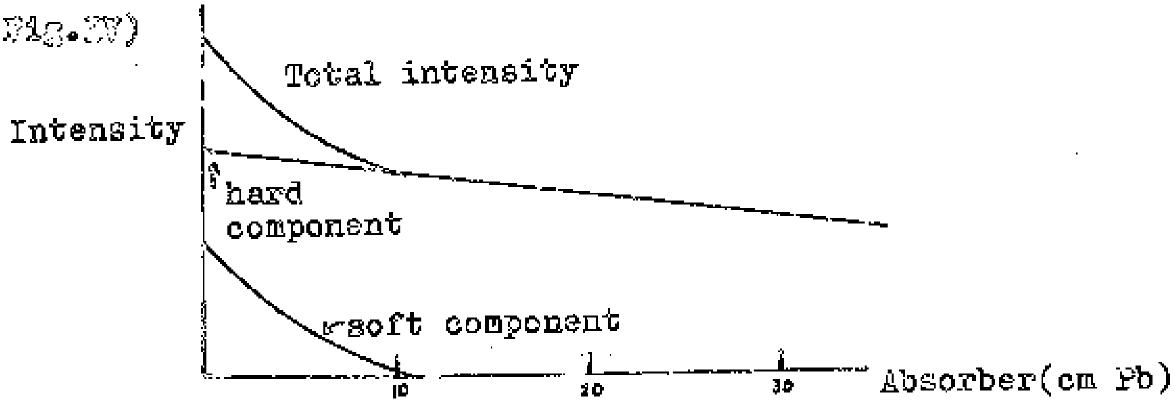


Fig.III Absorption curve of cosmic rays at sea level.
(After [illegible])

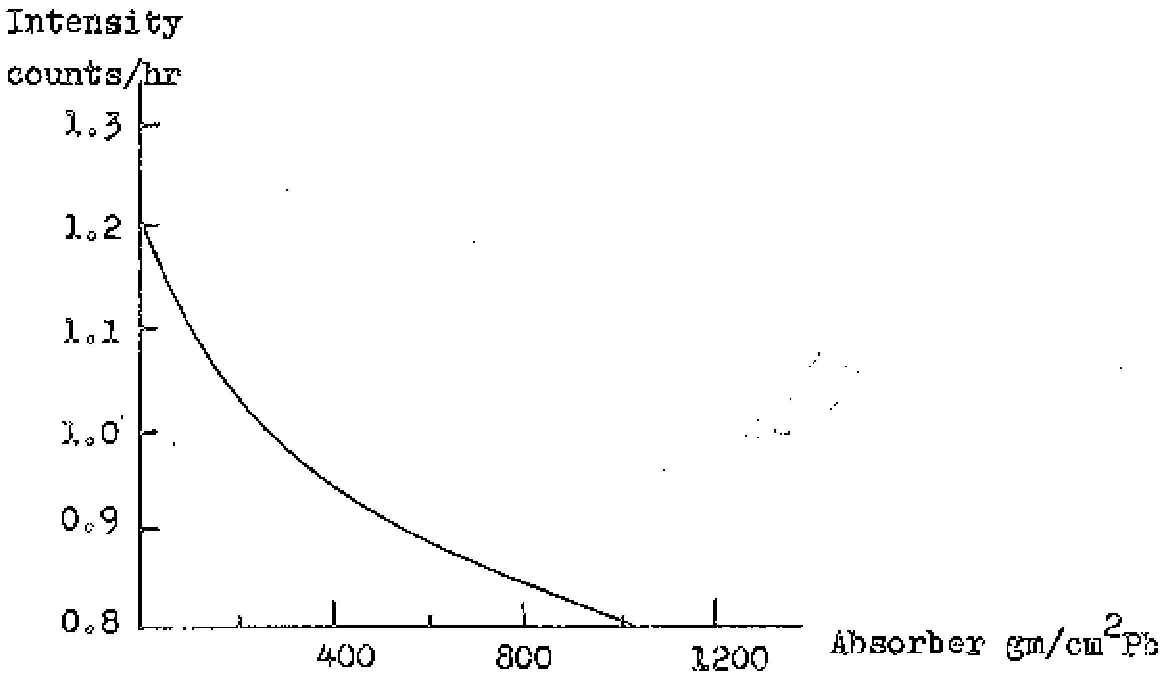


Fig.IV Absorption curve of cosmic rays, after Street(29).

b. Shower Component A number of observers have determined the absorption of shower components in lead. The absorption curve is referred to as a Rossi curve, shown by Cork(30), (See Fig.V)

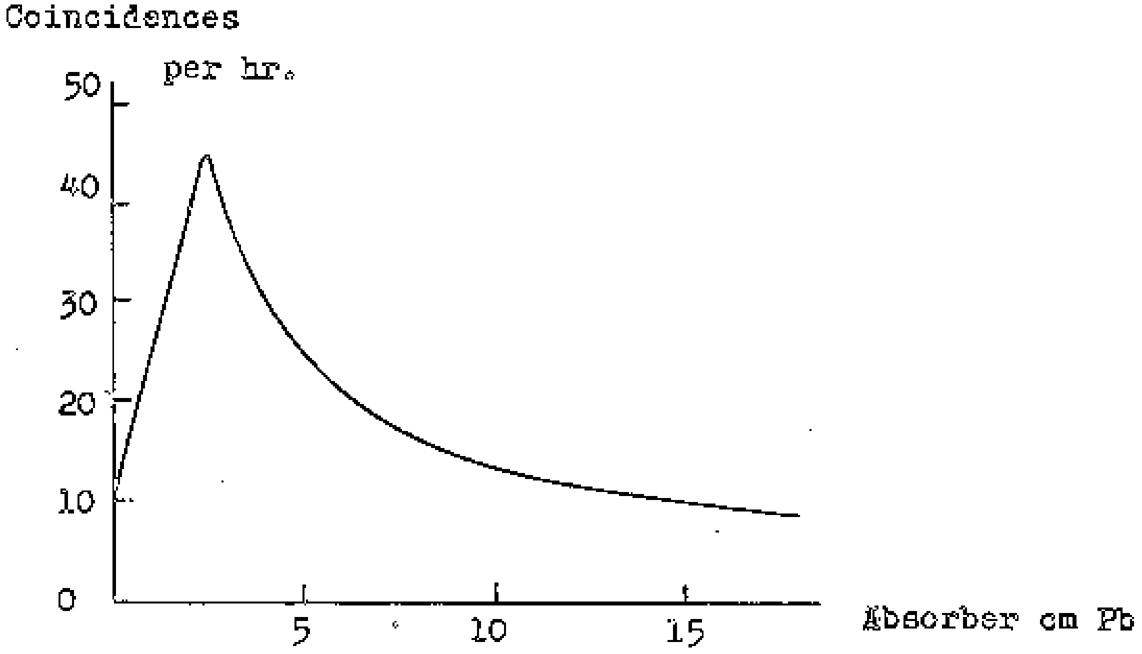


Fig.V Absorption of shower component in lead, after Cork(30)

The probability that a ray of a shower will penetrate a given thickness of lead was shown by Montgomery&Montgomery(31), as shown in Fig.VI.

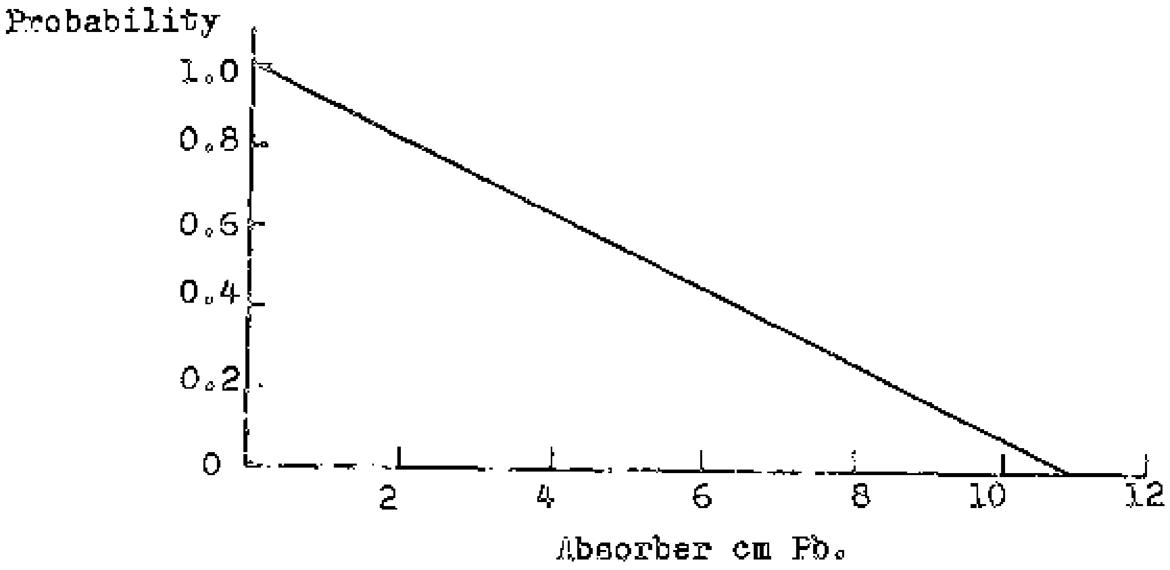


Fig.VI The probability that a ray of a shower will penetrate a given thickness of lead, after Montgomery(31).

c. <u>Star Producing Component</u>. George and Jason(22) have observed the absorption of the star producing component in lead;

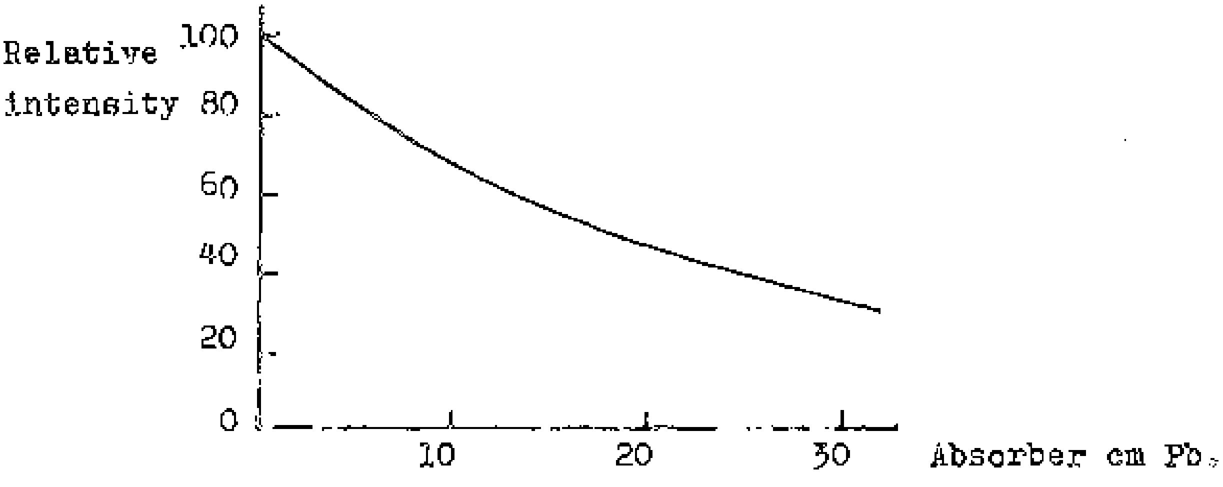


Fig.VII Absorption curve of the star intensity in lead, after George and Jason(22).

and obtained the absorption curve, as shown in Fig.VII .Then the experiment of Rodikov(39) by using cosmic ray telescope, the absorption curve of X-rays in lead was obtained, as shown in Rossi(4). (See Fig.VIII)

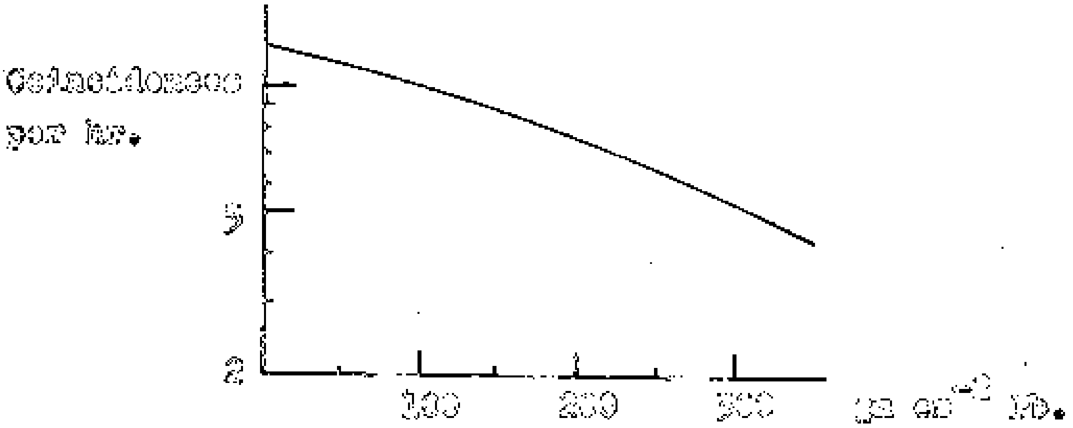


Fig.VIII Absorption curve of X-rays in lead, after Rossi(4).

III.7 Absorption Curve of Cosmic Ray at Different Altitude.

At high altitude the absorption curve of cosmic rays seems to be different from that at the sea level because of the increasing number of the soft component at sea level. Schein,M. and Yngve,V.H.(35) have studied the absorption at an altitude of 5.7 cm Hg. by using balloon flights with counters. The absorption curve in lead was obtained as shown in Fig.IX . A comparison of the two curves shows the difference in the composition of the cosmic radiation.The soft component increases by about the factor of 90 between sea level and an altitude of 5.7 cm Hg.

At sea level the flatness of the curve is due to the penetration of the hard component, predominantly mu-mesons. But at the altitude of 5.7 cm Hg the absorption is exponential with an absorption mean free path about 220 g cm^{-2} similar to that of high energy nucleons.

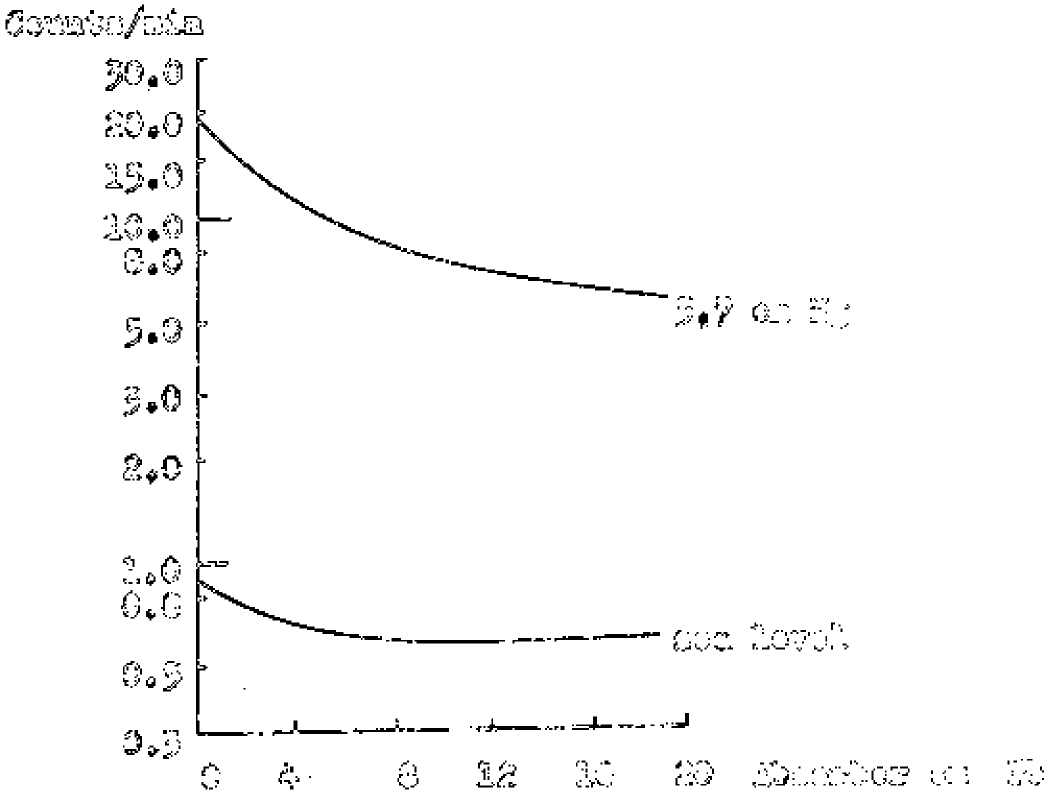


Fig.IX The upper curve gives the counting rate through several thicknesses of lead obtained at altitude corresponding to 5.7 cm Hg pressure. The lower curve gives the rate at sea level.(After Schein)