The Absorption Mean Free Path of the High Energy Nucleonic Component of Cosmic Radiation

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Two similar emulsion cloud chambers[1] consisting of 24 alternate 3mm lead plates and 25μ G-5 emulsions were exposed to the cosmic radiation. One stack was exposed for 30 days at 10,700 feet at Echo Lake, Colorado with the planes of the emulsions and lead plates at an angle of 45° with the vertical, the other was exposed for 6 hours at 90,000 feet at White Sands, New Mexico with the planes of the emulsions and lead plates horizontal. These two emulsion cloud chambers were used to obtain flux measurements of the nuclear interacting component of the cosmic radiation for energies $\gtrsim 10^{12}$ ev.; the data obtained was used to determine the absorption mean free path in the atmosphere (λ) for this energy region.

Since the emulsion cloud chamber is not a uni-directional detector, a Gross Transformation must be used in evaluating the data. Five nuclear interactions were observed in a systematic survey of 106 cm^2 of emulsion in the mountain stack, and fifteen such interactions were observed in a systematic survey of 45 cm^2 of emulsion in the high altitude stack. In each case the survey was made in an emulsion midway in the stack. The solution of the Gross Transformations for λ was obtained by forming a ratio of the transformation expressions for each plate assembly. Since the energy selection characteristics of these two stacks are the same, the ratio is not dependent upon the energy of the interactions. Energy determinations of the interactions were made by methods previously used for this type of exposure[1]. Figure 1 shows the expression involving the Gross Transformations of the two stacks, its solution, and the result obtained for λ. In the expression all quantities with subscript c refer to the high altitude stack, and all those with subscript m refer to the mountain stack. $N_{sc}(X_c)$ and $N_{sm}(X_m)$ represent the number of interactions observed in the two stacks at effective atmospheric depths X_c and X_m respectively. N_o is the primary interacting flux at the top of the atmosphere, the A's refer to the area of plate scanned for showers, and the T's are the times of exposure of the two stacks. t_c and t_m are the depths in the stacks of the point of observation. λ_1 represents the interaction mean free path of the combination of materials of the stacks, and $\alpha = 45^o$ the angle with the vertical of the mountain stack. θ is the azimuth angle of the incoming interacting particle, and θ_{min} and θ_{max} are limits imposed by the minimum observable track length in the plates.

The result for λ obtained here agrees with the majority of previous results obtained by other experimenters at lower energies[2]. (Contradictory results are given by Gottlieb[3] and Stinchcomb[4]). Our result taken with the generally accepted results at lower energies indicates that the absorption mean free path in atmosphere is independent of energy from $\sim 10^9$ ev to $\sim 10^{12}$ ev. Our result is inconsistent with the value calculated by Milford and Foldy[5] assuming completely inelastic nucleon collisions. Greisen and Walker[6] have suggested that a possible interpretation of such a long mean free path is that the fundamental act in the high energy component cascade is rather elastic.

Substituting the value of λ obtained here in the Gross Transformation for the high altitude stack, a value of the primary nucleonic flux at the top of the atmosphere of $N_o = .22 \pm .075$ per meter^2 per second per steradian was obtained. This result is in good agreement with that given by Kaplon and Ritson[1] for a somewhat higher energy. For a distribution of nucleons $\propto \cos^6\theta$ the integral primary flux of nucleons at mountain altitude was determined to be $N_o = .0009 \pm .0004$ per meter^2 per second per steradian. For comparison the integral primary flux of nucleons determined at mountain altitude assuming an isotropic distribution of nucleons was $N_o = .0004 \pm .0002$ per meter^2 per second per steradian. (This represents a lower limit on N_o at mountain altitude).

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$$\frac{N_{sc}(x_c)}{N_{sm}(x_m)} = \frac{N_0 A_c T_c \left(1-\exp-\frac{t_c}{\lambda_1}\right) \cdot 2\pi \int_{\theta_{min}}^{\frac{\pi}{2}} \sin\theta\cos\theta\, d\theta \exp-\frac{x_c}{\lambda\cos\theta}}{N_0 A_m T_m \left(1-\exp-\frac{t_m}{\lambda_1\cos\alpha}\right) 2\pi\sin\alpha \int_0^{\theta_{max}} \sin\theta\cos\theta\, d\theta \exp-\frac{x_m}{\lambda\cos\theta}}$$

In the solution of the above equation let the constants be represented by the ratio A/B. We have then:

$$\frac{A}{B} = \frac{\lambda^2\left(\exp-\frac{x_c}{\lambda\cos\theta_{min}}\left(1-\frac{x_c}{\lambda\cos\theta_{min}}\right)+\left(\frac{x_c}{\lambda\cos\theta_{min}}\right)^2\left(-Ei\left(-\frac{x_c}{\lambda\cos\theta_{min}}\right)\right)\right)}{\frac{\lambda\cos\theta_{max}}{x_m}\exp-\frac{x_m}{\lambda\cos\theta_{max}}\left(1-\frac{\lambda\cos\theta_{max}}{x_m}\right)-\frac{\exp-\frac{x_m}{\lambda}}{x_m}\lambda\left(1-\frac{\lambda}{x_m}\right)-Ei\left(-\frac{x_m}{\lambda}\right)+Ei\left(-\frac{x_m}{\lambda\cos\theta_{max}}\right)}$$

Solution of this expression with $\theta_{min} = 15^\circ$ and $\theta_{max} = 45^\circ$ gives $\lambda = 129 \pm 15$ grams/cm^2. The errors were determined from the statistical fluctuations in $N_{sc}(X_c)$ and $N_{sm}(X_m)$.

Figure 1: The determination of λ using the Gross Transformation