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Mean Free Path of Nuclear Interaction for High-energy Particles in Graphite

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The mean free path for nuclear interaction in graphite has been determined for high-energy charged particles in the case of the nucleonic component of cosmic radiation. In this experiment the absorbing material (graphite) was subdivided into three layers of equal thickness, and three trays of Geiger-Müller counters were inserted between them, for the purpose of eliminating the absorption effect of the secondary particles due to low-energy interactions occurring in the absorbent (Fig. 1(*a*) and 1(*b*)). If these are not recorded, they lead to a value in excess of the true mean free path. The latter might be one of the causes for which the experiments carried out by the method of primary absorption with a single-block absorbent led, for light materials, to values far greater than the geometric one.[1, 2, 3]

The experiment was conducted during the year 1955 in the laboratory of El Aguilar (Jujuy, Argentina), located at a height of 4000 m and a geomagnetic latitude of 11.5°S.

EXPERIMENTAL ARRANGEMENT

The geometrical arrangement (Fig. 2) is as follows. In the upper part there is a telescope T made up of the three upper trays of Geiger-Müller counters (A, B and C) on which the graphite has been distributed in three layers of equal thickness ranging from 0 g/cm^2 to 24 g/cm^2 during the experiment. In the lower part, the penetrating local shower detector ("P-set") made up of a layer of lead Σ_1 (productive layer) 100 g/cm^2 thick and two Geiger trays (D and E) separated by a thickness Σ_2 of lead (200 g/cm^2) to determine the minimum penetration of the particles of a shower were installed. Σ_1 and Σ_2 were maintained fixed during the whole of the experiment. Each one of the trays was made up of six metal counters 3 cm in diameter and 36 cm in effective length. The counters of the trays D and E were separated by lead plates 2 cm thick to reduce the effect of the "knock-on" electrons.

A selective circuit made it possible to distinguish any one of the following events in each one of trays A, B and C: (*a*) discharge of a single counter, (*b*) discharge of at least one counter, and (*c*) discharge of at least two counters. On the other hand, in the case of D and E, the selective circuits permitted recording of only the last two events.

Combining the various possibilities of the selective circuits it was possible to record such coincidences as (*a*) discharge of a single counter in A, B and C, and at least one in D and E (event T_1P^{11}); (*b*) discharge of a single counter in A, B and C and at least two in D and E (event T_1P^{22}); and (*c*) discharge of at least one counter in A, B, C, D and E (event T^1P^{11}).

The pulses from each Geiger-Müller counter of the trays D and E, on the one hand, contributed to the quintuple coincidence which produced the "master" pulse and, on the other hand, with the latter, they were brought to a hodoscopic system which, in part, made it possible to identify the tubes discharged in D and E. A panel with the neon lamps of the hodoscopic system, a mechanical recorder and a clock was photographed automatically when "master" T_1P^{22} was produced. The duration of the pulses in A, B and C was 4 μsec, in D and E, 10 μsec; the duration of the master pulse was 14 μsec, and the resolving time of the quintuple coincidence 5 μsec.

MEASUREMENTS CARRIED OUT

The frequency of the local penetrating showers produced in the Σ_1 layer of the "P-set" by an unaccompanied charged particle going through the telescope was measured for various total thicknesses of absorbent (0, 15, 30, 45 cm). For this purpose, event T_1P^{22} was recorded during most of the experiment. We also made auxiliary measurements which enabled us to carry out the necessary corrections, and, furthermore, we recorded for 972 hours, without any photograph, the event $A^1B^1C_1P^{22}$, for the purpose of making direct comparisons of the main results obtained with those which would be obtained using the single-block absorbent (since the more ample requirement A^1B^1 practically cancels out the presence of these trays).

The data obtained with master T_1P^{22} were classified, by investigation of the photographs, into events T_1P^{22}, T_1P^{32} and T_1P^{33}. This classification was carried out for the purpose of making a discrimination of the minimum energy of the primary which produced the

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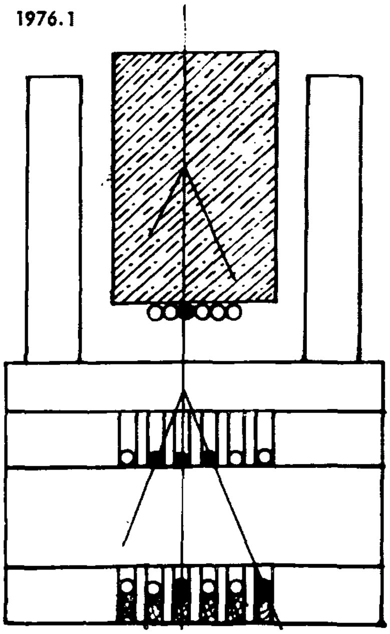

Figure 1(*a*). Penetrating local shower in productive layer, accompanied by a low-energy interaction which goes undetected (single-block graphite absorber)

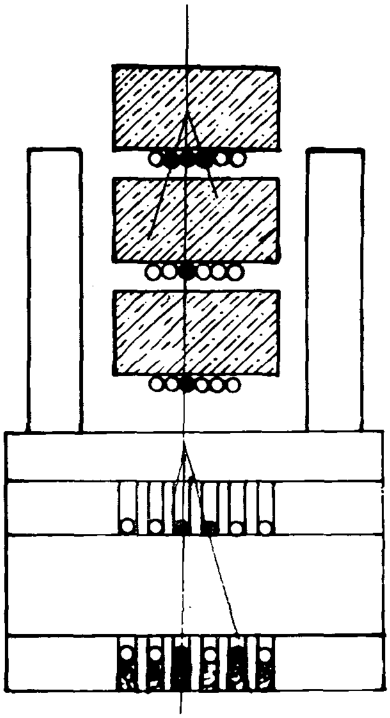

Figure 1(*b*). The same event as in Fig. 1(*a*), but the low-energy interaction is now detected (three-layer graphite absorber)

shower. The data of this experiment are the results of effective work of a 2600-hour team. The frequencies of the main events, without corrections, are shown in Table 1.

The measured frequencies were affected by spurious events, most of which were corrected by the customary process.[4] Such spurious events were:

(*a*) Production of "knock-on" electrons in trays D and E. In order to correct this, we used $T_1D^1E^1$, $T_1D^2E^1$ and $T_1D^1E^2$ masters.

(*b*) Accidental coincidence of a particle which goes through the whole of the device, laterally, with another one which only passes through the trays of the "P-set". We used, to make the correction, events T_1P^{11} and T_0P^{11} ($T_0P^{11} = T^0P^{11} - A^0B^0C_1P^{11}$).

(*c*) Local penetrating showers originating in the layer Σ_1 by nuclear interactions of μ mesons. Allowing for the fact that the μ mesons produce high-energy nuclear interactions having characteristics similar to those of the protons, but with a mean free path in lead 10^4 times greater,[5, 6, 7] we computed the contribution of these events to the frequencies measured,[4] obtaining:

$$N_\mu(x) = kN(0)F(x)$$

where $$N(x) = N_\mu(x) - N_N(x),$$

$$k = \frac{I_\mu(0)}{I_N(0)}\left[\frac{1-\exp(-\xi/\lambda_\mu)}{1-\exp(-\xi/\lambda_N)}\right] \quad (\xi = \text{thickness of } \Sigma_1).$$

Taking $I_\mu(0)/I_N(0) \cong 20$, $F(x)$ represents the relationship between frequencies T_1P^{11} recorded when the thicknesses of the graphite are x and 0 cm respectively.

(*d*) "Knock-on" electrons produced by the charged nucleonic component in the graphite of the telescope (Fig. 3). The presence of the trays of counters between the layers of absorbent and the requirements of the master increase the possibility that "knock-on" electrons produced in the absorbent by the proton component might cancel out the recording of actual events. In order to make the correction, events $T_1D^1E^1$, $A^2B_1C_1P^{11}$, $A_1B^2C_1P^{11}$ and $A_1B_1C^2P^{11}$ were recorded, which can be mostly ascribed to μ mesons.

With the events recorded, we determined the probability P_i of production of "knock-on" electrons by μ mesons in each one of the telescope trays, and therefore the total probability of "knock-on" electron production by μ mesons in the telescope, which we will indicate by

$$P = \Sigma\, P_i \quad (i = \text{A, B, C}).$$

According to the approximate formula of Ruther-

Table 1. Uncorrected Frequencies (hr^{-1})

Master	0 *cm C*	15 *cm C*	30 *cm C*	45 *cm C*
T_1P^{22}	1.67 ± 0.057	1.33 ± 0.057	1.13 ± 0.055	0.899 ± 0.044
T_1P^{32}	0.827 ± 0.040	0.698 ± 0.041	0.545 ± 0.038	0.401 ± 0.029
T_1P^{33}	0.372 ± 0.372	0.310 ± 0.028	0.245 ± 0.025	0.163 ± 0.019
$A^1B^1C_1P^{22}$	—	1.74 ± 0.13	1.30 ± 0.09	1.17 ± 0.10

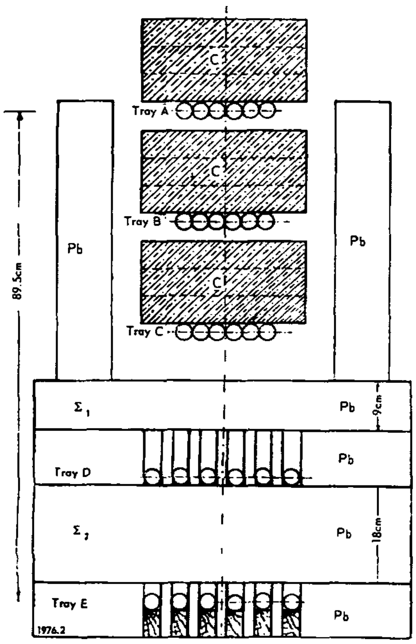

Figure 2. Geometrical arrangement of upper telescope T, and "P-set"

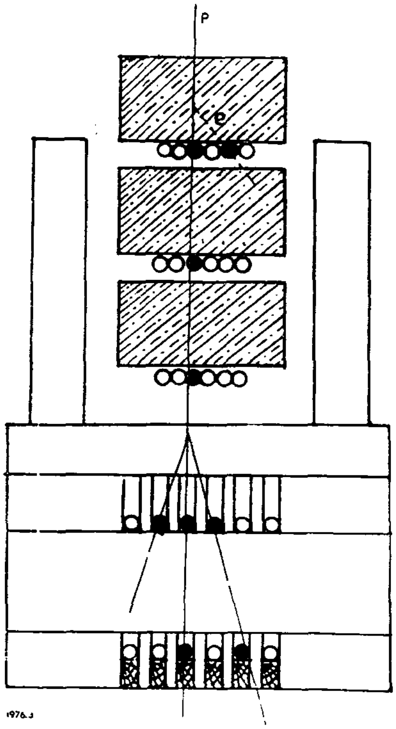

Figure 3. Penetrating local shower in productive layer Σ_1, accompanied by "knock-on" electron in the graphite

rd,[8] the relationship between the probabilities of production of "knock-on" electrons of the same energy for μ mesons and protons is in our case $\beta_\mu^2/\beta_N^2 = 0.96$. Therefore, the total probability of producing "knock-on" electrons by protons in the telescope will be $0.96P$ and, accordingly, the real frequency

$$N(x) = N'(x)/(1-0.96P),$$

where $N'(x)$ is the mean frequency at which the corrections mentioned above were made.

The values of the corrections are given in Table 2, the corrected results in Table 3 and their graphic representation in Fig. 4.

The mean free paths obtained according to the various energy requirements of the producing primary are given in Table 4.

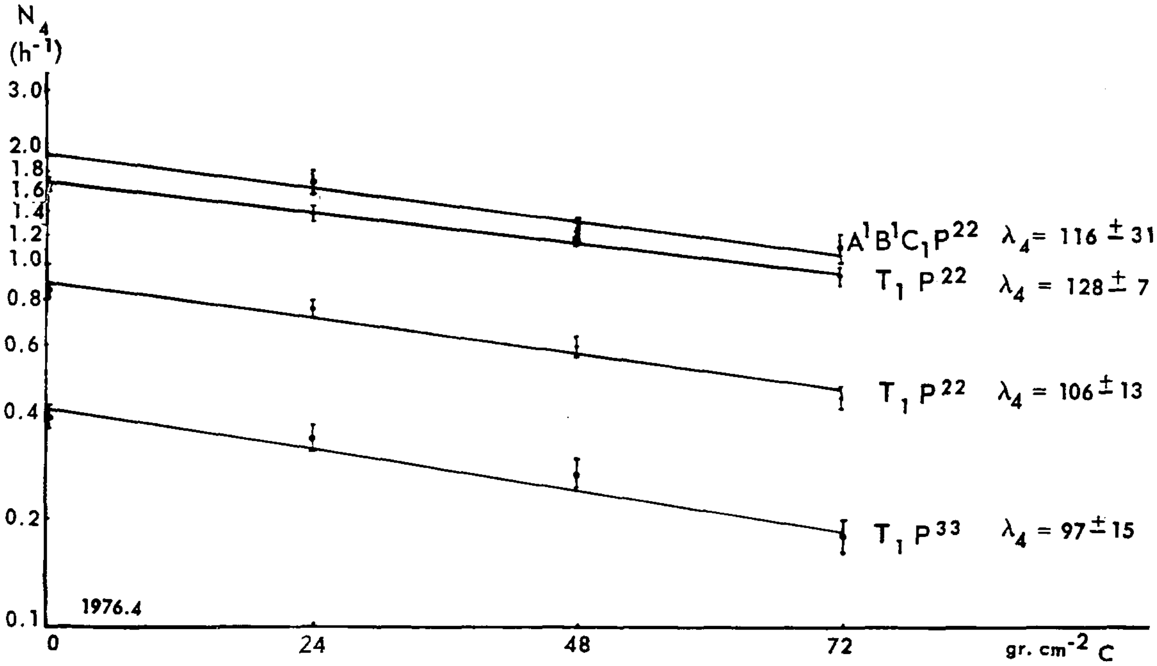

Figure 4. Frequency of local penetrating showers in Σ_1, corrected for spurious events

Table 2. Corrections in Percent[a]

Master	*Corrections*	0 *cm C*	15 *cm C*	30 *cm C*	45 *cm C*
T_1P^{22}	Double "knock-on"	2.0	2.4	2.4	3.0
	Coincidence μ	1.3	1.5	1.6	2.0
	"Shower" μ in P	0.3	0.3	0.4	0.5
	"Knock-on" in T	3.0	8.8	10.0	8.8
T_1P^{32}	"Shower" μ in P	0.3	0.3	0.4	0.5
	"Knock-on" in T	3.0	8.3	9.1	8.5
T_1P^{33}	"Shower" μ in P	0.3	0.3	0.4	0.6
	"Knock-on" in T	3.0	8.0	9.4	11.0
$A^1B^1C_1P^{22}$	Double "knock-on"	—	1.8	2.3	2.4
	Coincidence μ	—	1.0	1.0	1.4
	"Shower" μ in P	—	0.2	0.2	0.3

[a] We considered only the corrections in excess of 0.5%.

Table 3. Corrected Frequencies (hr^{-1})

Master	0 *cm C*	15 *cm C*	30 *cm C*	45 *cm C*
T_1P^{22}	1.66 ± 0.08	1.38 ± 0.07	1.18 ± 0.06	0.930 ± 0.05
T_1P^{32}	0.853 ± 0.010	0.752 ± 0.042	0.596 ± 0.038	0.433 ± 0.039
T_1P^{33}	0.383 ± 0.027	0.334 ± 0.028	0.268 ± 0.025	0.180 ± 0.019
$A^1B^1C_1P^{22}$	—	1.69 ± 0.13	1.25 ± 0.10	1.12 ± 0.10

EVALUATION OF THE ENERGY OF THE INCIDENT PARTICLE

From the experimental data, we endeavored to ascribe a minimum order of energy to the particle which produces each type of "shower". For this purpose, we tried to establish, from the number of counters discharged in each tray, a mean number of incident particles on the same. We used for this computation a Schrödinger criterion,[9] modified in our case by the fact that the counters of the trays considered were separated by 2-cm-thick lead plates. In addition, we assumed that the showers were being produced, on an average, in the center of symmetry of layer Σ_1. (For summary, see Table 5.)

We operated as follows: (1) From the number of counters discharged in tray E, we determined, for events T_1P^{22}, T_1P^{32} and T_1P^{33}, the mean number of particles incident on the same. (2) Since we had to determine a minimum order of energy we did not consider the effects of reproduction and absorption in the Σ_2 layer of the "P-set", which, for such a thickness, would imply that the number of the particles emerging is only 50% of those which impinged against the layer.[4] (3) In keeping with the assumption made regarding the mean zone of shower production, it was supposed that the incident particles on tray E were contained in a cone subtended by this tray, which contains only the two central counters of tray D. (4) We then computed the number of particles which impinge on the rest of tray D, and this, added to the above, gave us the actual mean number of incident particles. (5) We considered the relationship[10]

$$\tan^2\theta = (1/\gamma^2)\, F(\theta)/[1 - F(\theta)],$$

where γ is the energy of the incident particle in rest mass units in the center-of-mass system, and $F(\theta)$ is the fraction of particles produced in a nuclear interaction and projected within an angle having half-aperture θ. This relationship enables us to state that, for incident particles of energy 10 Gev or more, the fraction of secondaries projected within an angle having an opening equal to that subtended by tray D is of the order of 90%. (6) In order to determine the minimum energy from the number of particles produced in the shower, we used Messel's table,[11] which, for the range of energies which a priori we assume come into play in these events, coincides with experimental data of Camerini *et al.*[12]

Table 4. Corrected Values of the Mean Free Path (g/cm^2)

T_1P^{22}	T_1P^{32}	T_1P^{33}	$A^1B^1C_1P^{22}$
128 ± 7	106 ± 13	97 ± 15	116 ± 81

In this fashion, we could ascribe, to the particles which originate event T_1P^{22}, a minimum energy of 20 Gev.

Table 5

	T_1P^{22}	T_1P^{32}	T_1P^{33}
Mean number of Geiger-Müller counters discharged in tray E	2.51	2.65	3.45
Mean number of particles incident on tray E	4.00	4.23	6.18
Mean number of secondaries in the shower	5.56	6.18	8.00
Minimum energy of particles producing the shower (Gev)	20	30	55

For the other masters, we used the following reasoning: Since the integral spectrum of the primary component is conserved at the atmospheric depth at which we worked, we determined, from the frequency relationship between the various masters, what the energy ratio of the primaries produced by them should be, taking 1.5 as the exponent of the primary spectrum.[13]

We thus obtained, for the minimum energy of the particle which produced event T_1P^{32}, a value of 30 Gev, and for that of event T_1P^{33} 55 Gev.

CONCLUSIONS

From the results obtained, we find, in agreement with the observations made by other workers, that the mean free path decreases as the energy of the primary increases but, even for our highest energies, it is quite different from the geometric value. This would imply high values for nuclear transparency.

The comparison of the results obtained with events T_1P^{22} and $A^1B^1C_1P^{22}$ would indicate that the effect sought when subdividing the absorbent block into three layers is not manifested with the thickness used and for the geometry used in the experiment.

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