MEAN FREE PATH OF 10^{12}-eV NUCLEONS IN CARBON

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The mean free path for inelastic interactions of 10^{12}-eV nucleons in carbon is measured. The result, 92^{+12}_{-8} g/cm^2, is used to calculate the elementary cross section for inelastic nucleon-nucleon interactions which is found to be 33 ± 7 mb on the basis of the optical model. The results are compared with data obtained at lower energies.

THE mean free path for inelastic interactions of nucleons in light matter is one of the basic quantities required for calculating the passage of cosmic nucleons through the atmosphere. Great interest has recently been aroused in the asymptotic behavior of nucleon interaction cross sections in connection with theoretical indications that transparency to nucleons changes at high energies.[1] It can be expected that this change with increasing energy will lead primarily to an energy dependence of the mean free path for nucleon interactions in light matter.

The mean free path for inelastic nucleon interactions in carbon has been measured for $\sim 10^{10}$-eV nucleons by several investigators.[2-14] In [7-11] the experimental ratio of the mean free paths of nucleons in carbon and lead was determined. The mean free path in lead was taken as 160 g/cm^2. More precise measurements at an accelerator[14] and the latest measurements using cosmic rays[15, 16] have shown that the mean free path for inelastic interactions of 10^{10}-eV nucleons in lead is 200 g/cm^2. After the results of [7-11] are suitably corrected all measured values are grouped about 90 g/cm^2.

In the present work the mean free path of 10^{12}-eV nucleons was measured in airplane flights at 12 and 9 km. High-altitude measurements possess the advantage of a large intensity of high-energy nucleons with a relatively small accompaniment of the electron-photon and nuclear-active (n.a.) components. It is also important that at high altitudes nucleons comprise the great majority of the n.a. component.

The apparatus is represented in Fig. 1. Electron-photon cascades multiplying in the lead absorbers Pb_1, Pb_2, and Pb_3 were detected by rows II and III of ionization chambers. The uppermost row I enabled the discrimination of electron-

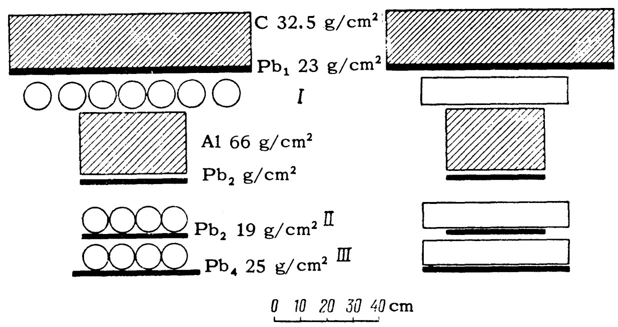

FIG. 1. Diagram of apparatus (two views).

photon cascades generated above this row; these were cascades arriving from the atmosphere and also cascades of π^0 mesons produced through nuclear interactions in the graphite block C. Cascades resulting from nuclear interactions in the aluminum block and adjacent matter induced no ionization in row I and can thus be isolated from the total number of cascades registered by the apparatus. Most of these nuclear interactions occurred in the aluminum block, which weighed 96 kg. An appreciable fraction of the interactions also occurred in matter weighing 90 kg between rows I and II.

The mean free path for interactions in graphite can be determined by using the familiar method of subtraction from the beam. The frequency N_1 of nuclear interactions in the absence of the block C and the frequency N_2 when an absorber of thickness l is placed above the apparatus are measured, giving

$$L = l/\ln(N_1/N_2). \quad (1)$$

Cylindrical ionization chambers 10 cm in diameter and 55 cm long were filled with argon to 6 atm. Pulses from the chamber plates, amplified 1.5×10^3 times were fed to oscillograph tubes which registered the total ionization in row I, the total ionization in row II, and the ionization in each chamber of row III. The driven sweep was triggered when more than 200 electrons traversed the chambers of row II simultaneously with more than 400 electrons in row III. Row I did not control the apparatus.

The stability of the apparatus was monitored carefully. The state of the gas in the chambers was monitored by observing pulses induced by α particles from polonium deposited on the chamber walls. Twice each month the gas pressure was checked and the amplification channels were carefully calibrated. Before each flight we checked the gains of the amplification channels, the radio noise level, and the threshold pulse triggering the apparatus. Five calibrated pulses from the monitor circuit were photographed successively during the operation of the apparatus in flight. The heights of these pulses were selected to cover the entire range of the registered pulses.

Evidence for the stability of the apparatus was found in the constant counting rate of cascades. For example, during the first run without absorber C from March to June, 1960 the counting rate was 95 ± 3 cascades per hour, while from June to August, 1961 the rate was 93 ± 3. The error of ionization measurements determined from the error spread of calibrated pulses, was about 6%.

The energy of electron-photon cascades was determined from the ionization induced in chambers of row III. The number of particles was converted to cascade energy in accordance with cascade theory. Cascades generated in the aluminum block passed through matter having an average thickness equivalent to 9 radiation units. For the broad energy interval from 10 to 300 BeV cascades at this depth are found close to the maximum of their development,[17] where a linear relation exists between the number of particles and the cascade energy.

Table I gives the ratio of the ionization J_2 in row II to the ionization J_3 in row III for cascades impinging on the apparatus from the air. The ratios J_2/J_3 in Table I pertain to cascades traversing 8 and 12 radiation units in the lead absorbers. These data were obtained with apparatus not containing C and Al blocks. Table I indicates that the cascades were close to their maximum development in the entire energy interval.

The energy E of an electron-photon cascade with account taken of the transition effect in the chamber walls [18] is related to the number of particles in the chambers by

$$E\,(\text{BeV}) = 0{,}1N. \qquad (2)$$

For nuclear interactions in the apparatus the energy of an electron-photon cascade is the energy of all the produced π^0 mesons. In calculating the energy of nucleons it was assumed, in agreement with [19], that

$$E_{\text{nucl}} = 7{,}4E_{\pi^0}. \qquad (3)$$

In using Eq. (1) it is assumed that all registered cascades are induced in the apparatus by nucleons passing through the volume occupied by the graphite absorber. However, a certain number of cascades could have been produced by particles which, because of the imperfect experimental geometry, did not pass through the upper row of chambers. The number of these "background" events did not vary with the inclusion of the absorber, and in computing the mean free path for interactions this number must be subtracted from both N_1 and N_2.

To determine the number of background events we computed the geometric factors given in Table II for the registration of different kinds of events. In calculating the geometric factors we followed [20] in taking the dependence of cascades on the zenith angle θ as $\sim\cos^2\theta$ at 12 km and $\sim\cos^3\theta$ at 9 km. The data in Table II show that nucleons inducing local nuclear interactions in the apparatus passed through the graphite absorber C.

The background events could thus represent electron-photon cascades entering the apparatus from the atmosphere at large zenith angles. The intensity of the background events was calculated in accordance with the geometric factors in Table II, taking account of the known intensity of electron-photon cascades. The correction for background events was 8% of N_1 at 12 km and 13% at 9 km. Data obtained in control experiments with apparatus not containing an aluminum block also furnished evidence that the number of background events was small.

Table I. Values of J_2/J_3

No. of particles in cascade	800—1100	1100—1600	1600—2200	2200—4800	4800—16000
12 km	0.94±0.04	1.12±0.06	1.02±0.05	1.03±0.05	1.11±0.13
9 km	1.01±0.03	1.11±0.04	1.07±0.07	1.18±0.09	1.10±0.14

Table II. Values of ΩS (m^2 - sr)

Altitude, km	12	9
For particles inducing nuclear interactions in the apparatus	0.074	0.069
For particles traversing the carbon absorber	0.10	0.09
For electron-photon cascades from the atmosphere	0.11	0.10

Table III

Absorber	Al		Al + C		Control experiment	
Altitude, km	12	9	12	9	12	9
Measurement time, hrs	17.2	20.2	25.0	22.2	17.5	18.2
Total number of cascades	1750	865	2270	944	1480	850
Cascade counts per hour	102±2	43±1.5	91±2	42±1.4	85±2	47±1.6
Number of nuclear interactions per hr	51.0±1.7	17.6±0.9	36.4±1.2	13.4±0.8	26.3±1.2	9.4±0.8

Table IV

	Control experiment	Nuclear interactions	Electron-photon cascade
Ratio of intensities at 12 km and 9 km	2.6±0.2	2.62±0.13	1.51±0.07
Exponent of energy spectrum 12 km	1.89±0.15	1.87±0.11	1.47±0.08
Exponent of energy spectrum 9 km	2.03±0.31	1.91±0.20	1.34±0.10

If all matter were removed from the space between rows I and II in which nuclear interactions occur, the cascades not inducing ionization in row I would be background events. However, the removal of the aluminum block did not completely exclude nuclear interactions, since in this way only about half of the matter between rows I and II was removed. The number of registered cascades dropped to approximately half upon removal of the aluminum block (Table III), the great majority of these cascades being induced by nuclear interactions. This is shown by: 1) the distribution of ionization in chambers of row III (Fig. 2), 2) the altitude dependence of cascade intensity (Table IV), and 3) the shape of the cascade energy spectrum (Table IV).

It is also noteworthy that the ionization peak is observed in middle chambers more often than in end chambers by the factor 1.35 ± 0.10, whereas the opposite should be observed for the background events.

The basic experimental data are given in Table III for cascades in which the number of particles is double the threshold number. This was done in order to exclude the influence of instability of threshold ionization. For the purpose of excluding instrumental instability the flights with absorber C were alternated with flights lacking the absorber. The last line of Table III gives the intensity of cascades for which ionization in row I did not exceed the ionization due to 30 relativistic particles.

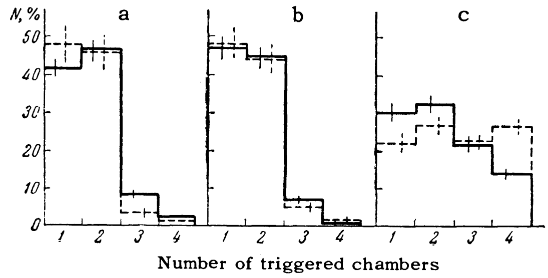

FIG. 2. Distribution of ionization (number of triggered ionization chambers in row III). Abscissa – number of chambers in which ionization exceeded 1/4 of maximum: a) in control experiment, b) in nuclear interactions within apparatus, c) in electron-photon cascades from the atmosphere. Continuous line – measurements at 12 km; dashed line – at 9 km.

The fraction of $\pi^{\pm}$ mesons in the flux of the n.a. component could not be determined experi-

Table V. Ratio of nuclear interaction frequency in the absence (N_1) and presence (N_2) of the C block

Nucleon energy, BeV	N_1/N_2				Mean free path, g/cm^2
	12 km	9 km	Average	With correction for background events	
>600	1.40±0.06	1.31±0.10	1.37±0.05	1.43±0.06	92^{+12}_{-8}
>850	1.40±0.08	1.25±0.12	1.36±0.07	1.40±0.08	97^{+20}_{-14}
>1200	1.33±0.11	1.18±0.17	1.29±0.09	1.34±0.11	110^{+40}_{-20}
>1700	1.64±0.20	1.34±0.25	1.55±0.15	1.62±0.17	68^{+20}_{-12}

mentally. The $\pi^\pm$ flux was determined [21] from data on the muon flux. According to the computations the $\pi^\pm$ flux above 10^{12} eV is about 10 particles/m^2-hr-sr at the 200-g/cm^2 level. The number of nuclear interactions induced by this $\pi^\pm$ flux is about 1% of the registered interactions. Since at depths 200—300 g/cm^2 the flux of high-energy nuclei is negligible, the nuclear interactions registered by the apparatus were induced by nucleons.

The intensity ratios N_1/N_2 for nucleons of different energies are given in Table V. To determine the mean free path we used a weighted average of the data obtained at the two altitudes. The same table gives the mean free path for inelastic interactions after a correction for background events. The computed mean free path corresponds to interactions in carbon where π^0 mesons receive at least 0.5% of the nucleon energy.

By varying the criterion of nucleon subtraction from the beam through the selection of interactions associated with different amounts of ionization in chambers of row I, we obtained the dependence of the mean free path on the fraction of energy transferred to π^0 mesons. This relation, represented in Fig. 3, shows that the number of interactions with low energy transfer to π^0 mesons in small; therefore the error due to overlooking interactions transferring less than 0.5% of the nucleon energy to π^0 mesons is unimportant.

The mean free path for inelastic interactions of 10^{12}-eV nucleons in carbon is 92^{+12}_{-8} g/cm^2. This result coincides with the mean free path at 10^{10} eV. This constancy of the mean free path is accounted for if the transparency to nucleons remains small up to $\sim 10^{12}$ eV. With this assumption the optical model [22] can be used to calculate the elementary nucleon-nucleon cross section σ_0, taking the spatial distribution of nucleons in the carbon nucleus from [23]. The foregoing value of the mean free path corresponds to an elementary

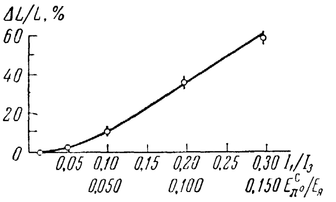

FIG. 3. Mean free path L for interaction vs. the fraction of energy transferred to π^0 mesons. I_1/I_3 is the corresponding ratio of pulse heights in rows I and III.

cross section $\sigma_0 = 33 + 7$ mb for inelastic interactions, which agrees with direct measurements of the elementary cross section at about 2.5 × 10^{10} eV.[24]

An enhancement of transparency to nucleons with increasing energy cannot be excluded, however. In this case a constant elementary cross section should be accompanied by the observation of a reduced mean free path. For a sufficiently large transparency the mean free path will not depend on the atomic number [1] and will be represented by

$$L = 1/\sigma_0 N, \tag{4}$$

where N is Avogadro's number. To account for the constant mean free path we must then assume that the elementary cross section diminishes as the transparency to nucleons increases. In the limiting case (4) the mean free path corresponds to the elementary cross section 18 mb. A choice between the two foregoing possibilities could be based on a comparison of the mean free paths in different elements.

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