INELASTIC INTERACTION BETWEEN COSMIC RAY PROTONS OF KINETIC ENERGY ABOVE 7 Bev AND CARBON AND HYDROGEN NUCLEI

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Inelastic interaction between cosmic ray protons of kinetic energy above 7 Bev (mean energy ~ 20 Bev) and carbon and hydrogen nuclei was investigated at a geomagnetic latitude of 31° N in the stratosphere. The measurements were made with a telescope containing absorbers of lead and of the investigated graphite and paraffin. A system of hodoscopic counters surrounded the telescope and the absorbers. A value of 315 ± 50 millibarns was obtained for the proton-carbon inelastic-interaction cross section. The proton-proton inelastic interaction cross section was 32 ± 10 millibarns. The average number of charged penetrating particles was found to be 4.2 ± 0.5 particles per shower in carbon and ~ 3.4 particles per shower in hydrogen.

1. INTRODUCTION

THE study of absorption of beams of nuclear-active particles in cosmic rays[1] and of the formation of various secondary cosmic-ray components in the atmosphere[2] has led in its time to the conclusion that the interaction between nucleons and light nuclei have low inelasticity in the energy range from 2 to 1,000 Bev. In connection with this, it has been suggested by Vernov[3] that the observed low inelasticity of the interaction discloses a certain structural feature of the nucleon, namely that it has a denser central portion and less dense peripheral portion. Experiments on the scattering of 1.4-Bev pions by protons, performed in 1955,[4] lead to similar conclusions.

A study of the inelasticity of interaction between nucleons and nuclei is thus found to be one of the effective means of investigating the structural properties of the interacting particles. It must be emphasized here that the value of the coefficient of inelasticity of interaction obtained in references 1 and 2 depends substantially on the effective cross section for inelastic interaction between the nucleons and the nuclei of the atoms in the atmosphere. This cross section was assumed to equal the geometric cross section. It was therefore quite important to measure this cross section for cosmic-ray particles in the region of energies, for which collisions with light nuclei were found to be of low inelasticity.

Directly connected with problems in the interaction of high-energy particles with light nuclei is the study of the dependence of the number of particles generated upon interaction on the atomic weight of the nucleus and on the energy of the incident particle. It is equally important to determine the effective cross section of inelastic proton-proton interaction and its energy dependence.

In the present article we report the measured effective cross sections of inelastic interaction between primary cosmic rays (protons with kinetic energy greater than 7 Bev) with carbon and hydrogen nuclei[5-8] and the measured number of particles generated in these interactions. The experiments were performed in the stratosphere at an altitude of 20 to 25 km and a geomagnetic latitude 31°N, for there the proton energy spectrum is cut off on the low side of 7 Bev, and diminishes as the 1.5 power with increasing energy (integral spectrum). The apparatus developed made it possible to measure the interaction cross section by two different methods, to measure the number of particles produced by interaction, and to determine the current of primary particles with greater procedural reliability than previously.

2. MEASUREMENT METHOD AND APPARATUS

Two methods were used in this work to determine the inelastic-scattering cross section.

Method I. The cross section was determined from the reduced flux of single shower-producing protons as the latter pass through the investigated absorber. The flux is reduced by inelastic interactions between the protons and the atomic nuclei of the investigated matter. The relative reduction in the flux is determined in this method by the

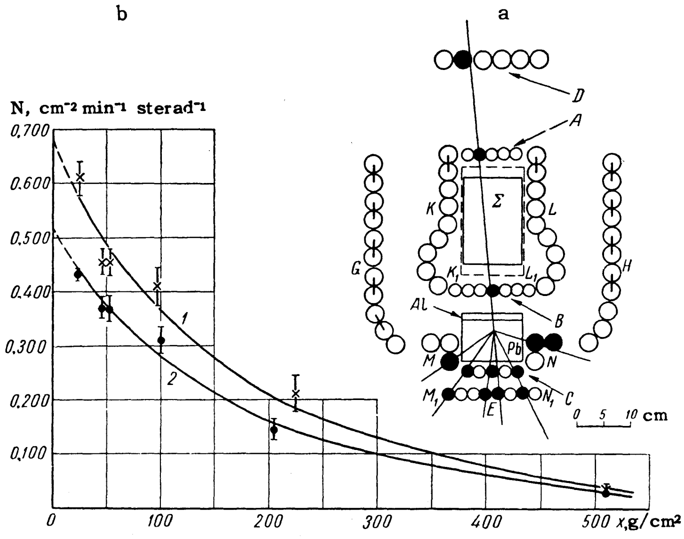

FIG. 1. a) Arrangement of counters and absorbers in the instrument and counter operation in the shower, b) Number of showers of lead measured as follows: 1) without graphite absorber in telescope, 2) with 16.8 g/cm² graphite in the telescope.

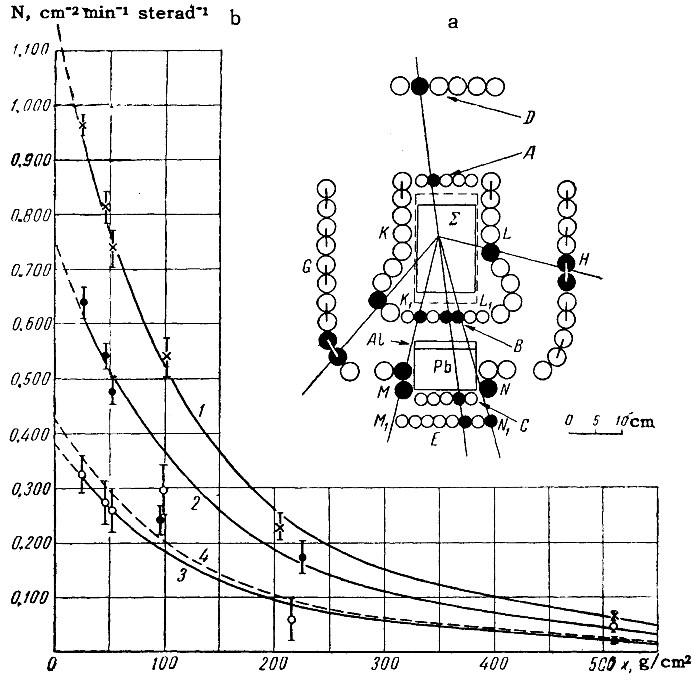

FIG. 2. a) Arrangement of counters and absorber in the instrument and counter operation in the shower. b) Curves: 1) number of showers in upper part of the instrument when measured with graphite absorber (16.8 g/cm²); 2) the same without graphite absorber (background); 3) difference between curves 1 and 2; 4) number of interactions in carbon N_{intC}, with allowance for corrections.

change in the number of electron-nuclear showers from a lead indicator over which the investigated absorber is placed.

Method II. The cross section is determined by directly measuring the number of electron-nuclear showers occurring in the investigated matter when nuclear-active particles pass through the latter.* To determine the cross section by this method it is necessary to know, in addition to the number of electron-nuclear showers from the investigated substance, also the flux of shower-producing protons I_x at a given depth of the atmosphere x. This flux can be determined if we know the flux I_0 of the primary protons, arriving from cosmic space at the boundary of the atmosphere, and we know the absorption range of the shower-producing component in the air, L_{abs}^{air} (L_{abs}^{air} is determined from the altitude dependence of the electron-nuclear showers in lead).[6]

Thus, to solve our problem with the aid of the above two methods, we had to measure in the stratosphere, as accurately as possible, the number of electron-nuclear showers in paraffin, graphite, and lead. It was also necessary to determine the altitude dependence of the particle flux of the hard component which, when extrapolated to the top of the atomosphere, yields the flux* I_0 of the primary protons. Based on these requirements, we selected apparatus that separated, the hard component of cosmic rays with the aid of lead. To obtain good geometrical conditions with respect to separation of the hard components, we placed the lead indicator of our instrument in the lower portion of a rather long telescope, thanks to which the possibility of registering the so-called "additional" showers in lead due to particles moving outside the solid angle of the instrument.†

The placement of the counters and absorbers in the instruments used to determine the cross section of inelastic interaction is shown in Figs. 1a and 2a. The vertical telescope consisted of

*Owing to the large extent of the atmosphere at low density of matter, the nuclear-active components in the stratosphere with energies below 10^{11} ev are almost exclusively nucleons, since the charged pions with energies less than 10^{11} ev decay before they interact with the nuclei of the air atoms.

*By extrapolating to the top of the atmosphere we found the flux of primary particles at latitude 31°N (longitude 73°E) to be I_0 = 2.0 to 2.1 particles/cm²-min-sterad.[6] Winkler et al[9] found at a depth of 15 g/cm² (geomagnetic latitude 30°N) a value $I_{x=15}$ = 2.7 to 2.8 particles/cm²-min-sterad with a 3-cm lead absorber. Extrapolation of Winkler's data to the top of the atmosphere where the flux of the primary particles at the boundary of the atmosphere at latitude 30°N a value I_0 = 2.1 to 2.2 particles/cm²-min-sterad, i.e., a value very close to ours.

† The "additional" showers due to particles traveling outside the solid angle of the instrument cause coincidences of discharges in telescopic counters only because shower particles enter into these counters.

three rows A, B, C of self-quenching Geiger-Mueller counters, (five counters in each row) connected for three-fold coincidence. Row D of hodoscopic counters, placed at a certain distance above the Geiger counters, covered almost the entire solid angle of the instrument. An absorber comprising 8 cm of lead and 0.9 cm of aluminum was placed between rows B and C of the telescopic counters. Absorber Σ of the investigated substance was placed between rows A and B of the telescopic counters. The solid lines in the diagram show the placement of an absorber made of powdered graphite (volume density $d \approx 1.0$ to $1.1\ g/cm^3$; density per unit absorber surface $d_1 = 16.0\ g/cm^2$). The dotted line shows the position of a paraffin absorber ($d \approx 0.95\ g/cm^3$; $d_1 = 18.8\ g/cm^2$). The absorbers were interchanged automatically every three minutes. The telescope and the absorbers were surrounded by a large number of counters (K, K_1, L, L_1, M, M_1, N, N_1, E, G, H),* which served to register the charged particles produced by interaction between the protons and carbon, hydrogen, and lead nuclei. All counters,† including the telescopic ones, were connected to a vacuum-tube hodoscope.

The pulse controlling the operation of the instrument was produced by three-fold coincidence of the discharges and counters A, B, and C. However, when processing the measurement results, we took into account only those cases where the triple coincidence was accompanied by operation of one of the counters in row D, i.e., four-fold coincidences. The instrument readings were telemetered to the earth and recorded on motion-picture film by a photoregister. The resolution of the telescope was 3×10^{-6} seconds; the resolution of the hodoscopic numbers (which was different for different counter groups) ranged from 1×10^{-5} to 2×10^{-5} seconds. The instruments, their characteristics, the method of hodoscope data processing, and the methods used to introduce various corrections in the measurement results are all described in references 6 to 8.

The results published in this article were obtained by launching five instruments in pilot balloons into the stratosphere in September 1955.

*In the processing of the results we disregarded the counter rows G, and H, which were used only to monitor the operation of counters K and L.

†The dimensions of the counters are given in reference 6. The counters were filled with a mixture of argon and ethylene. The negative electrode was a thin graphite layer deposited on the inner surface of the glass walls of the counters. The counter glass wall was 1.0 to 1.5 mm thick.

Two of these instruments contained a graphite absorber and an absorber comprising 8 cm lead and 0.9 cm aluminum in the telescope, two contained absorbers of paraffin and graphite and a Pb + Al absorber, and one contained absorbers of paraffin and graphite without a Pb + Al absorber in the telescope.

3. USE OF METHOD I TO DETERMINE THE RANGE AND CROSS SECTION FOR INELASTIC INTERACTION BETWEEN A PROTON AND A CARBON NUCLEUS

Using hodoscopic counters, we were able to investigate cases where a singly-charged particle (proton) traversed the upper portion of the telescope (through absorber Σ) without interacting and without experiencing inelastic interaction in the lead block. We selected here the events in which the particles of the shower produced in the lead entered only into counters C, E, M, M_1, N, and N_1, located in the lower portion of the instrument around the lead (showers produced in lead without upward-moving particles). The selection method employed is illustrated by the shower in lead shown in Fig. 1a (the counters operated by the passage of the particles are denoted by the filled-in circles). The number of such showers in lead is proportional to the flux of single shower-producing particles incident on the lead. When the graphite is placed in the telescope the flux diminishes in accordance with the reduction in the flux of single shower-producing particles. An analysis of the counters operated in the showers has shown that these showers contain practically no non-local shower impurities (not more than 4%).

Figure 1b shows the measured number of showers in lead in the presence of graphite in the telescope, (N^C_{sPb}, curve 2) and without graphite (N^b_{sPb}, curve 1) at different depth x of the atmosphere. The curves were corrected for random coincidences and for δ showers (the correction for the δ showers in lead was the same with and without graphite in the telescope and its numerical value was $(6.85 \pm 0.12)\%$ of the number of single particles registered at a given altitude[6-8]). The statistical errors are indicated for all points of the curves. To increase the statistical accuracy of the determined cross section for the interaction with carbon we also used, when plotting the curves, the results of a series of measurements with graphite and paraffin with an approximate account of the shower production in hydrogen. The effective thickness of the graphite absorber, for the

TABLE I. Range and cross section of inelastic p-C interaction as measured by method I.

Depth of atmosphere, x, g/cm²	Showers in lead: without graphite in telescope N^b_{sPb}, cm⁻² min⁻¹ sterad⁻¹	Showers in lead: with graphite* in telescope N^C_{sPb} cm⁻² min⁻¹ sterad⁻¹	N^C_{sPb}/N^b_{sPb}	L^C_p, g/cm²	σ^C_p, mbn
53.0	0.452±0.026	0.369±0.024	0.816±0.070		
46.7	0.454±0.024	0.370±0.019	0.815±0.059		
25.0	0.609±0.029	0.431±0.012	0.709±0.039		
Average 33.7			0.754±0.030	63^{+12}_{-9}	315±50

*Effective thickness of graphite 16.8 g/cm².

combined data, was 16.8 g/cm². From the data given in Fig. 1b it is possible to determine the range L^C_p for the inelastic interaction between a proton and carbon nucleus, using a formula that accounts for the fraction of α particles in the primary cosmic radiation:

$$N^C_{sPb}/N^b_{sPb} = p\exp\{-16.8/L^C_p\} + \alpha\exp\{-16.8/L^C_\alpha\}. \quad (1)$$

Here p and α are the fractions of the protons and α particles at altitudes 20 to 25 km, and L^C_α is the interaction range of an α particle in a light substance, assumed here as 40 g/cm². The number of primary α particles at the top of the atmosphere was assumed to be 20% of the total number of primary particles. The correction for the interaction due to α particles was approximately 5% of the value of the cross section.

The range L^C_p and the cross section σ^C_p for inelastic interaction between protons and carbon nuclei, obtained by the above method in the altitude range from 20 to 25 km, was found to be (see Table I):

$$L^C_p = 63^{+12}_{-9}\ \text{g/cm}^2;\ \sigma^C_p = 315 \pm 50\ \text{millibarns}.$$

It must be noted that the cross section of inelastic interaction as determined by the above method includes automatically interactions with proton charge exchange and with formation of only neutral fast particles; it also includes events of shower production by charged particles with a wide angle of divergence, when not one charged particle enters the lower row of telescopic counters.

4. USE OF METHOD II TO DETERMINE THE RANGE AND CROSS SECTION OF INELASTIC INTERACTION BETWEEN A PROTON AND A CARBON NUCLEUS

The showers of the particles that are produced by interaction between protons and carbon nuclei are identified by operation of the counters that are immediately adjacent to the graphite filter (counters K, K_1, B, L_1, L) independently of the operation of the counters located near the lead, i.e., they are classified as showers registered in the upper portion of the instrument.[6] An example is the event shown in Fig. 2a.

We determine the range of inelastic interaction from the relation

$$N_{\text{int C}} = I_x p(1 - \exp\{-16.8/L^C_p\}) + I_x\alpha(1 - \exp\{-16.8/L^C_\alpha\}). \quad (2)$$

Here $I_x = I_0\exp(-x/L^{air}_{abs})$ is the flux of shower-producing particles at a given depth x of the atmosphere, I_0 is the flux of primary particles on the top of the atmosphere at the geomagnetic latitude 31°N, L^{air}_{abs} is the absorption range of the shower-producing component in the air, and $N_{\text{int C}}$ is the number of nuclear interactions in carbon.

Figure 2b shows the altitude dependence of the showers registered in the upper portion of the instrument by the counters that surround directly the graphite absorber, obtained with a graphite absorber (N^C_s, curve 1) and without it (N^b_s, curve 2). These curves have been corrected for random coincidences and for δ showers (the corrections are respectively (7.00 ± 0.20)% and (3.00 ± 0.15)% of the total number of registered single particles with and without graphite in the telescope[6-8]). The statistical errors are indicated for all points of the curves. Curve 3 of Fig. 2b represents the difference between curves 1 and 2. Curve 4 was obtained from curve 3 by introducing corrections for the change in the number of showers in lead with upward-directed particles, when changing from measurements with graphite to measurements without graphite (correction for the variation in the "backward current," see references 6 and 7), and for the entrance of shower

TABLE II. Measured range and cross section for inelastic p-C interaction by method II.

Depth of atmosphere, x, g/cm²	Showers in upper portion of instrument: with graphite* N_s^C cm⁻² min⁻¹ sterad⁻¹	without graphite (background) N_s^b cm⁻² min⁻¹ sterad⁻¹	$N_s^C - N_s^b$	Flux of shower-producing particles I_x for $I_0 = 2.0$	$\frac{N_s^C - N_s^b}{I_x}$	Correction for change in "backward current"	Correction for slits	$\frac{N_s^C - N_s^b}{I_x}$ with corrections	L_p^C, g/cm²	σ_p^C, mbn
53.0	0.741±0.034	0.482±0.027	0.258±0.043	1.402	0.184±0.030					
46.7	0.815±0.028	0.542±0.026	0.274±0.038	1.467	0.186±0.026					
25.0	0.964±0.018	0.638±0.029	0.326±0.034	1.683	0.193±0.020					
Average 33.7					0.190±0.014	+0.015	+0.010	0.215±0.014	76±7	264±24

*Effective thickness of graphite 18.8 g/cm².

particles into the slit between counters (see Table II). To determine the cross section with our data, we took the flux of primary particles on the top of the atmosphere of latitude 31°N to be $I_0 = 2.0$ particles/cm²-min-sterad (reference 6) and the range of absorption of a shower-producing component in air to be L_{abs}^{air} 150 g/cm² (reference 6).

Using this method we obtain the following values for the range and for the cross section of inelastic p-C interactions (see Table II):

$$L_p^C = 76 \pm 7 \text{ g/cm}^2; \sigma_p^C = 264 \pm 24 \text{ millibarns}.$$

The cross section obtained by direct observation of showers in graphite thus turned out to be some 20% less than the value obtained from the reduction in the flux of single shower-producing particles. It is possible that this difference is explained essentially by the fact that when the protons interact with the carbon nuclei, approximately 10 or 15% of the events are accompanied by interactions without a shooting off of high energy charged particles (π^0 mesons and fast neutron).[10,11] It is also possible that charged-particle showers with wide divergence angles are produced, so that not a single charged particle enters into the lower row C of the telescopic counters. These events are missed by the instrument in the direct observation of showers in the graphite, but are registered by the first of the methods described. The indicated fraction of such interactions is quite probable, if we consider that the showers observed in graphite consist in approximately 30% of the cases of two charged particles. Comparison with the measured values of the cross section, obtained by other authors[12-14] by diverse methods, also indicates a possible error in counting the interactions in determination of the proton-carbon nucleus cross section by direct observation of showers in graphite.

5. CROSS SECTION OF INELASTIC PROTON-PROTON INTERACTION

We investigated the inelastic proton-proton interaction as the difference between proton interactions in paraffin and in graphite. Both aforementioned methods were used to determine the cross section for inelastic proton-proton interactions. Production of a shower that consists of only neutral fast particles is considerably less probable in proton-proton interactions than in collisions between a proton and a complex nucleus. The method of direct observation of showers on hydrogen can therefore be considered practically free of interaction counting errors due to production of fast neutral particles alone. This is in contrast

TABLE III. Results of measurement of range and cross section of inelastic p-p interaction

Instrument	Method	Average depth of atmosphere, x, g/cm²	Ratio of fluxes I_{par}/I_{gr}	L_p^H, g/cm⁻²	σ_p^H, mbn
No. 3 with absorber 8 cm Pb + 0.9 cm Al	II	36.4	0.905 ± 0.033		
No. 5 with absorber Pb + Al	II	25.9	0.948 ± 0.030		
No. 7 without lead absorber	II	42.5	0.981 ± 0.028		
No. 3 with absorber 8 cm Pb + 0.9 cm Al	I	36.4	0.866 ± 0.058		
No. 5 with Pb + Al absorber	I	25.9	1.000 ± 0.060		
	Average	34.0	0.947 ± 0.060	51^{+23}_{-12}	32 ± 10

Note: Amount of hydrogen in paraffin 2.8 g/cm².

with what takes place in the determination of the cross section for the interaction between protons and carbon nuclei. We have determined the cross section from flight data with two instruments (Nos. 3 and 5) with paraffin, graphite, and lead absorbers and with one instrument (No. 7) with paraffin and graphite absorbers, but without a lead absorber in the telescope.

For approximate standardization of the conditions of registration of the electron-nuclear showers produced in the paraffin and graphite, we used powdered graphite. The graphite and paraffin absorbers were placed in the telescope with their centers aligned (see Figs. 1a and 2a). The thickness of the graphite absorber, in g/cm², was equivalent to the amount of carbon, in the paraffin absorber, also in g/cm².

We have calculated the cross section for inelastic proton-proton interaction from the ratio of the fluxes of single shower-producing particles obtained with paraffin and graphite in the telescope (I_{par} and I_{gr} respectively). This ratio is related to the range L_p^H of inelastic proton-proton interaction by the equation

$$I_{par}/I_{gr} = \exp(-2.8/L_p^H); \tag{3}$$

where 2.8 is the amount of hydrogen in paraffin (g/cm²). The interaction due to primary α particles was negligible.

In the method of direct observation of showers in paraffin (N_s^{par}) and in graphite (N_s^{gr}), the flux ratio is obtained by measuring the quantity $(N_s^{par} - N_s^{gr})/I_{gr}$, since $I_{par}/I_{gr} = 1 - (N_s^{par} - N_s^{gr})/I_{gr}$. Here $I_{gr} = I_x \exp(-x' L_p^C) = I_0 \exp(-x/L_{abs}^{air}) \exp(-x' L_p^C)$ is the flux of single shower-producing particles at a given depth x of the atomosphere, attenuated by interaction with carbon nuclei in the paraffin absorber, and x′ is the carbon in the paraffin in g/cm². To determine I_{gr} we used our following data: 1) I_0 = 2.0 particles/cm²-min-sterad;[6] 2) L_{abs}^{air} = 150 g/cm²;[6] 3) L_p^C = 63 g/cm² (sec. 3; see also reference 7).

In the method that makes use of the reduction in the flux of single shower-producing particles, the flux ratio is obtained by measuring the number of showers in lead in the presence of paraffin (N_{sPb}^{par}) and graphite (N_{sPb}^{gr}) in the telescope: $I_{par}/I_{gr} = N_{sPb}^{par}/N_{sPb}^{gr}$.

Table III shows the values of the ratio of fluxes of single shower-producing particles, I_{par}/I_{gr}, obtained with various instruments and diverse methods. These values include the corrections (see references 6 and 8). The statistical errors are indicated in all cases.

After averaging all the data given in the table, with allowance for the statistical weights, the range L_p^H and cross section σ_p^H of inelastic proton-proton interaction become:

$$L_p^H = 51^{+23}_{-12}\ \text{g/cm}^2 \quad \sigma_p^H = 32 \pm 10 \ \text{millibarns}$$

Figure 3 shows the cross section for inelastic

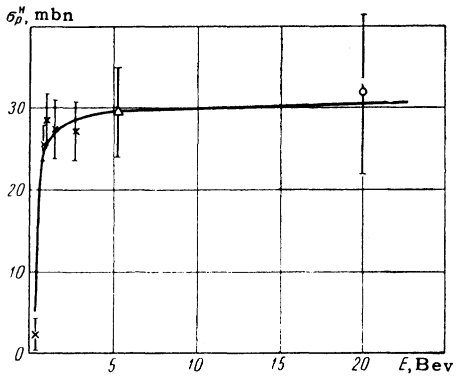

FIG. 3. Effective cross section of proton-proton inelastic integration vs. kinetic energy of incident proton. × – data of reference 15, obtained with accelerators, △ – Wright et al.[16] o – Alekseeva and Grigorov.[5,8]

proton-proton interaction as a function of the kinetic energy of the incident proton, plotted from data obtained with accelerators[15,16] and from our own data obtained with cosmic-ray protons of kinetic energy > 7 Bev ($\bar{E} \approx 20$ Bev). This curve shows that, within the limits of statistical experimental errors, no considerable change in the cross section for inelastic proton-proton interaction is observed in the energy interval from 1 or 2 to approximately 20 Bev.

At energies on the order of several Bev we can estimate the nucleon interaction in peripheral collisions from a calculation of the interaction of their π-meson fields by the Weizsaecker-Williams method. Such an estimate was made by Bubelev,[17,18] who used experimental[3,4] values of the scattering cross section and of the radius of the nucleon core.[15] In the energy range from 1 to 10 Bev, Bubelev's calculations yield a constant effective cross section for inelastic peripheral nucleon collisions. If we take Bubelev's calculations, then our experimental data, which suggests a constant effective cross section for inelastic interactions up to energies of ≈ 20 Bev, lead to the conclusion that, in the energy range from 1 or 2 to ~ 20 Bev, the contribution of central collisions to the value of the cross section remains constant and does not exceed $\sim 20\%$.

6. NUMBER OF PARTICLES IN ELECTRON-NUCLEON SHOWERS, OBTAINED ON LIGHT NUCLEI AT ENERGIES 10^{10} ev.

By analyzing the operation of the counters directly adjacent to the investigated absorber Σ (counters K, K_1, B, L_1, and L; Fig. 2a) we were able to determine the distribution of the showers of particles in carbon and hydrogen from the number of operating counters; we were also able to determine the average number of counters operated per shower. The shower particles registered by the counters consisted essentially of penetrating particles (the energy of the π mesons registered by the counters surrounding the absorber Σ was $E_\pi \gtrsim 50$ Mev).

Figure 4 shows the distributions of the electron-nuclear showers over the number n of counters operated per shower (over the number of particles in the shower), obtained by us and by the authors of reference 20, as a percentage of the total number of registered electron-nuclear showers with $n \geq 2$. Curve 1 gives the distribution of electron-nuclear showers in carbon, as obtained from the number of

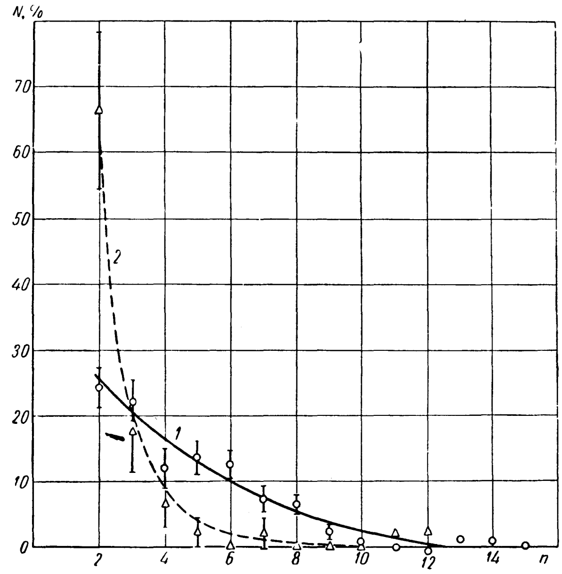

FIG. 4. Distribution of electron-nuclear showers with more than 2 charged particles with respect to the number of particles n in the shower, as a percentage of the total number of counted showers. 1) showers in carbon, according to Alekseeva and Grigorov; 2) showers in beryllium according to Baradzei, Smorodin, et al.[20]

counters operated in the shower,* for an altitude of 20 to 25 km at geomagnetic latitude 31°N. To improve the statistics in plotting this curve, we used the combined data of all the instruments lifted to the stratosphere, both with graphite absorbers and with graphite and paraffin absorbers, with a lead absorber in the telescope. The measurement results were corrected for random coincidences and for δ showers. Curve 2 of Fig. 4 gives the measured number of penetrating particles in showers in beryllium, obtained by Baradzei, Smorodin et al.[20] with the aid of a cloud chamber at an altitude of 9 km and geomagnetic latitude 51°N. These results are free of the influence of the control signal on the shower selection, since the chamber would operate by passage of even one charged particle through the instrument. We see that our shower spectrum differs substantially from the spectrum obtained in reference 20 (curve 2). This difference in spectra cannot be attributed to the difference in the atomic weights of the investigated substances (carbon and beryllium), since these atomic weights are close to each other. There is also little likelihood that the difference in the spec-

*In those cases when two counters in rows K and L could be operated by passage of a single particle (operation of two in-line counters in the middle of rows K and L), these two counters were regarded as a single counter.

tra is due to differences in the apparatus.*

The difference between our spectrum and that obtained by the authors of reference 20 (see Fig. 4) is apparently due to difference in the energy spectra of the shower-producing protons.

We obtained the following values for the average number of operated counters (average number of penetrating particles) in showers with $n \geq 2$ particles at an average energy of shower-producing protons $\overline{E} \sim 20$ Bev: $\overline{n} = 4.2 \pm 0.5$, and $n \approx 3.4$ particles per shower for carbon and hydrogen, respectively (see Table IV).

Comparison of the average number of charged π mesons in showers with $n \geq 2$ in beryllium, at an average kinetic energy of shower-producing protons $\overline{E} \sim 6$ Bev (reference 20 and 21), with the value we obtained for the average number of charged π mesons in showers from carbon at an average proton energy $\overline{E} \sim 20$ Bev (see Table IV) gives an approximate dependence $\overline{n} = k\overline{E}^m$, where $m \sim 0.3$.

At energies $\sim 10^{10}$ ev, the production of π mesons by nucleon-nucleon interactions is treated by the statistical theory of multiple-particle production. The principal conclusions of this theory, with allowance for the nucleon isobar states that arise during the interaction, are discussed in reference 22. It would be interesting to compare our experimental data on the number of particles produced in p-C and p-p interactions with the deductions of the statistical theory of multiple-particle production in nucleon-nucleon interactions. Inasmuch as we deal in stratosphere measurements with proton spectra that are different at different altitudes, we have calculated, for the sake of comparing the experimental results with the theoretical deductions, the average number of charged particles (p, π^+, π^-) per shower in p-p interactions for the primary-proton spectrum in the stratosphere at geomagnetic latitudes 31°N ($\overline{E}_{kin} \sim 20$ Bev) and 51°N ($\overline{E}_{kin} \sim 6$ Bev). The calculations were based on the results obtained by the authors of reference 22, with allowance for the fluctuation in the number of charged particles produced in the shower.* This number was found to be, respectively, 3.8 and 3.0 particles (p, π^+, π^-) per shower. The number of protons per shower, according to the calculations, was 1.1. Unfortunately, the presence of additional apparatus-induced fluctuations in the experimentally-obtained distribution of showers with respect to the number of particles has made it impossible to make a correct comparison between the theoretical and experimental particle-number spectra of showers.

The calculated values of the average number of charged π mesons produced in p-p interaction, and also the experimental data on the average number of charged particles and charged π mesons in showers with $n \geq 2$, are compared in Table IV for hydrogen,[16] beryllium,[20] and carbon and hydrogen (our data). It follows from the table that, within the limit of the statistical accuracy of the experiment, the experimentally-determined average number of charged π mesons produced by p-p interaction agrees, for the energy spectra of the primary protons at latitudes 31°N and 51°N with the number calculated on the basis of the statistical theory of multiple particle production with account of the isobar states of the colliding nucleons. Going from hydrogen to the light nuclei Be and C, the number of charged π mesons in the shower (shown in the last column of Table IV), for interactions between nucleons and light nuclei, is approximately 1.2 or 1.3 times the number of charged π mesons in nucleon-nucleon interac-

*The effect of errors in counting showers with $n = 2$ particles, resulting from shower particles entering into the same counter, was relatively small in our experiments, since for the cosmic-ray proton spectrum at the latitude 31°N the production of showers with $n = 2$ charged particles is less probable than production of showers with $n \geq 3$ (for the proton spectrum at latitude 51°N to the contrary, a shower with $n = 2$ is more probable). In addition, for each class of showers, the loss in showers due to transition to a class with a smaller number of particles n is compensated for, to a considerable extent, by the showers from classes with higher values of n.

*Since the theoretical curves of the relative probability of production of n particles by inelastic proton collision in the energy range from 1 to 20 Bev are well approximated by the normal-distribution curve with a constant $h = 0.32 \pm 0.58\, E_{kin}^{-0.5}$ Bev, the average number of charged particles were determined for the proton spectra indicated above by graphically integrating the expression:

$$\overline{n}_{p\pi^\pm} = \sum_{n=2}^{n=1} n F_1(n)/F_2, \tag{4}$$

where

$$F_1(n) = \int_{E_{kin}^{min}}^{\infty} \frac{Ah}{(E_{kin}+1)^{2.5}\sqrt{\pi}} \exp\{-h^2[n - \overline{\overline{n}}(E_{kin})]^2\}\, dE_{kin},$$

$$F_2 = \int_{E_{kin}^{min}}^{\infty} \frac{A}{(E_{kin}+1)^{2.5}}\, dE_{kin};$$

A is a constant, and $\overline{\overline{n}}(E_{kin})$ is the most probable number of particles per shower for a given proton energy E_{kin}. All the supplementary data of the theoretical investigations of S. Z. Belen'kiy, V. M. Maksimenko, A. I. Nikishov, and I. L. Rozental' needed for these calculations, were graciously supplied by V. M. Maksimenko.

TABLE IV. Average number of particles in showers with n ≥ 2 particles, produced by interaction between a proton and a light nucleus and between two protons

Average proton energy	$\overline{E}_{kin}$ ~ 6 Bev		$\overline{E}_{kin}$ ~ 20 Bev	
Interaction	p – p	p – Be	p – p	p – C
Experimentally-obtained average number of charged particles in shower (π mesons and protons)	3.2 ± 0.6[16]	3.0 ± 0.5[20]	~ 3.4*	4.2 ± 0.5*
Correction for protons	– 1.1**	– 0.6***	–0.8***	– 0.8***
Average number of charged π mesons in shower (experiment)	2.1	2.4	2.6	3.4
Average number of charged π mesons in shower, according to statistical-theory data for the energy spectra of incident protons	1.9		2.7	
Ratio of number of charged π mesons in shower in interactions between a nucleon and a light nucleus and in nucleon-nucleon interactions	1.26		1.26	

*Our data.
**Correction in accordance with statistical-theory data.
***Correction in accordance with Smorodin's data for showers in beryllium.[21]

tions at the same energy. From a comparison of the experimental data with the results of the statistical-theory calculations it follows apparently that at energies $\sim 10^{10}$ ev there is little likelihood of considerable production of independent successive nucleon-nucleon interactions within the light nucleus.

CONCLUSIONS

1. The measured values of the range and of the cross section for inelastic interactions between protons and carbon nuclei are, respectively $L_p^C = 63_{-9}^{+12}$ g/cm^2 and $\sigma_p^C = 315 \pm 50$ millibarns. This means that, within the limits of experimental accuracy, the latter equals the geometric cross section of the carbon nucleus.

2. The respective values obtained for proton-proton interactions are $L_p^H = 51_{-12}^{+23}$ g/cm^2 and $\sigma_p^H = 32 \pm 10$ millibarns. In the energy range from 1 or 20 Bev, there is no noticeable change in the proton-proton inelastic cross section, within the limits of experimental accuracy.

3. The average number of penetrating particles in electron-nuclear showers is $4.2 \pm 0.5 \sim 3.4$ particles per shower, in carbon and hydrogen respectively, at an average proton energy of ~ 20 Bev. The dependence of the average number of π mesons in the shower on the average energy of the incident proton varies approximately as the 0.3 power of the energy, in the range from 6×10^9 to 2×10^{10} ev. The calculated number of charged π mesons produced in p-p interactions, calculated on the basis of the statistical theory of multiple particle production which account of the isobar states of the colliding nucleons, equals the experimentally-determined number.

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