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Fig. 1

Figure 1: Fig. 1

Abstract

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PHYSICS

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THE CROSS SECTION FOR THE INELASTIC INTERACTION OF PROTONS WITH KINETIC ENERGY ABOVE 7 BeV WITH ATOMIC NUCLEI OF CARBON

(Presented by Academician D. V. Skobeltsyn, 15 I 1957)

This article gives the results of a measurement of the cross section for the inelastic interaction of protons with carbon nuclei at geomagnetic latitude 31°N in the stratosphere (1), in the region of those energies for which we had earlier found a small inelasticity of collisions with light nuclei (2).

The instruments for measuring the cross section of inelastic interaction (see Figs. 1a and 2a) consisted of a telescope (rows of counters D, A, B, C), surrounded by a large number of hodoscopic counters for recording secondary particles from interactions in graphite and lead (the counters D, A, B, C were also connected to the hodoscope). Between rows B and C there was a filter of 8 cm of lead and 0.9 cm of aluminum. Into the space between counters A and B

Fig. 1. 1 —number of showers from lead in measurements without a graphite filter in the telescope; 2 —number of showers from lead in measurements with graphite (16.8 $\mathrm{g \cdot cm^{-2}}$) in the telescope

every 3 min the filter Σ under study was inserted or withdrawn—crushed graphite (density 1.0–1.1 $\mathrm{g \cdot cm^{-3}}$, thickness 16.0 $\mathrm{g \cdot cm^{-2}}$)*.

A detailed description of the instruments for determining the interaction cross section was given in paper (3). To determine the cross section we used experimental data corresponding to altitudes > 20 km. A rough estimate shows that we determined the cross section for a flux of protons, among which 80% had kinetic energy greater than 7 BeV; of the latter

* The solid line indicates the position of the graphite filter inside the telescope; the dashed line, the position of the paraffin filter.

about 3/4 had a mean energy of ~ 12 BeV. The cross section for inelastic proton-carbon-nucleus interaction was determined by two methods.

Table 1

Atmospheric depth x, g · cm^{-2}	Atmospheric depth x, g · cm^{-2}	Showers from lead: without graphite in the telescope $N^{\Phi}_{\text{sh. Pb}}$, cm^{-2} · min^{-1} × sterad^{-1}	Showers from lead: with graphite* in the telescope $N^{C}_{\text{sh. Pb}}$, cm^{-2} · min^{-1} × sterad^{-1}	$\frac{N^{C}_{\text{sh. Pb}}}{N^{\Phi}_{\text{sh. Pb}}}$	$\frac{N^{C}_{\text{sh. Pb}}}{N^{\Phi}_{\text{sh. Pb}}}$	Inelastic interaction path L_p^C, g · cm^{-2}	Inelastic interaction cross section σ_p^C, mb
53.0	33.7	0.452 ± 0.026	0.369 ± 0.024	0.816 ± 0.070	0.754 ± 0.030	63^{+12}_{-9}	315 ± 50
46.7	33.7	0.454 ± 0.024	0.370 ± 0.019	0.815 ± 0.059	0.754 ± 0.030	63^{+12}_{-9}	315 ± 50
25.0	33.7	0.609 ± 0.029	0.431 ± 0.012	0.709 ± 0.039	0.754 ± 0.030	63^{+12}_{-9}	315 ± 50

* Graphite thickness 16.8 g · cm^{-2}.

1. Method of reducing the flux of the shower-producing component upon passage through graphite.

With hodoscopic counters we were able to study such cases in which a single charged particle (proton) passed without interaction through the upper part of the telescope (through the first three rows of counters D, A, and B, located above the lead filter) and underwent an inelastic interaction in the lead block. In doing so we selected only those cases in which the particles of the shower produced in the lead entered only the counters C, E, M, M_1, N, N_1, located in the lower part of the apparatus near the lead (so-called showers without "back current" of particles). An illustration of the selection method we used is the shower from lead shown in Fig. 1a (the counters that fired during the passage of particles

Fig. 2. 1 —number of showers in the upper part of the apparatus in measurements with a graphite filter (16.8 g · cm^{-2}); 2 —number of showers in the upper part of the apparatus in measurements without a graphite filter (background);

Fig. 2

Figure 2: Fig. 2

3 —difference of curves 1 and 2; 4 —true number of interactions in graphite, with all corrections taken into account $N_{\text{int C}}$.

counters are indicated by black circles). The number of such showers from lead is proportional to the flux of single shower-producing particles incident on the lead, and decreases when graphite is placed in the telescope in accordance with the decrease in the flux of single non-shower-producing particles.

In Fig. 1b are shown the results of measuring the number of interactions in lead in the presence of graphite in the telescope $N^C_{\text{in Pb}}$ (curve 2) and without it $N^\Phi_{\text{in Pb}}$ (curve 1) at various depths in the atmosphere. The curves shown have been corrected for random coincidences and for δ-showers*. Everywhere the root-mean-square statistical error is indicated**.

From the data presented in Fig. 1b, one can determine the mean free path L_p^C and the cross section σ_p^C of inelastic proton–carbon-nucleus interaction, using a formula that takes into account the fraction of α-particles in primary cosmic radiation:

$$\frac{N^C_{\text{in Pb}}}{N^\Phi_{\text{in Pb}}} = pe^{-16.8/L_p{}^C} + \alpha e^{-16.8/L_\alpha{}^C}; \qquad \sigma_p^C = \frac{A_C}{N_{\text{Av}} L_p^C}.$$

Here p and α are the fractions of protons and α-particles at an altitude of 20–25 km; L_α^C is the interaction mean free path of α-particles in light matter, equal to 40 $\text{g} \cdot \text{cm}^{-2}$. N_{Av} is Avogadro' s number. The number of primary α-particles at the boundary of the atmosphere was taken to be 20% of the total number of primary particles.

As we see, this method does not require knowledge of the true value of the flux of shower-producing particles or of the true number of interactions in lead. The correction for interactions by α-particles amounts to about 6% of the value of the cross section. In addition, with the method we adopted for selecting showers from lead, they prove to be practically free from admixture of nonlocal showers (^{3}).

The value of the mean free path and of the cross section for inelastic interaction of protons with carbon nuclei, obtained by the method described above in the altitude interval 20–25 km, was found to be

$$L_p^C = 63^{+12}_{-9}\ \text{g} \cdot \text{cm}^{-2}; \qquad \sigma_p^C = 315 \pm 50\ \text{mb}.$$

(see Table 1).

* The percentage of δ-showers from lead in the presence of graphite and without graphite in the telescope was the same and equal to (6.85±0.12%) of the number of registered single particles.

** To increase the statistical accuracy in determining the interaction cross section with carbon, the curves were also constructed using the data we had from measurements with graphite (16.0 $\text{g} \cdot \text{cm}^{-2}$) and paraffin (18.8 $\text{g} \cdot \text{cm}^{-2}$), with approximate allowance for shower production in hydrogen. The effective thickness of the graphite filter for these combined data was found to be 16.8 $\text{g} \cdot \text{cm}^{-2}$.

Table 2

Atmospheric depth x, $\text{g} \cdot \text{cm}^{-2}$	Showers in the upper part of the device with graphite N^C_{sh}, min^{-1}	Showers in the upper part of the device without graphite (background), N^{Φ}_{sh}, min^{-1}	Shower-producing particle flux $I = I_0 e^{-x/150}$, at $I_0 = 2.0$ $\text{cm}^{-2} \text{min}^{-1} \text{sr}^{-1}$	$\frac{N^C_{\text{sh}} - N^{\Phi}_{\text{sh}}}{I}$	Correction for change in "backward" current	Correction for interaction of particles in lead	Correction for all interactions in lead	Mean free path of the inelastic interaction L^C_p, $\text{g} \cdot \text{cm}^{-2}$	Cross section of the inelastic interaction σ^C_p, mb
53.0; 46.7	0.741± 0.034	0.482± 0.027	1.402	0.184± 0.030	+0.015	+0.040	0.245± 0.014	76±7	264± 24
33.7	0.815± 0.028	0.542± 0.026	1.467	0.186± 0.026	+0.015	+0.040	0.245± 0.014	76±7	264± 24
25.0	0.964± 0.018	0.638± 0.029	1.683	0.193± 0.020	+0.015	+0.040	0.245± 0.014	76±7	264± 24
25.0	–	–	–	0.190± 0.014	+0.015	+0.040	0.245± 0.014	76±7	264± 24

* Thickness of graphite 16.8 $\text{g} \cdot \text{cm}^{-2}$.

2. Method of direct observation of inelastic interactions in a graphite filter

(by the number of showers from mesons produced in the graphite). We determine the interaction mean free path from the relation

$$N_{\mathrm{int}C} = I_p \left(1 - e^{-16.8/L_p^C}\right) + I_\alpha \left(1 - e^{-16.8/{L_\alpha}^C}\right).$$

As we see, the method requires knowledge of the true value of the flux I of shower-producing particles and of the true number of interactions in the graphite.

Showers of particles arising in the interaction of protons with carbon nuclei are selected by the triggering of counters directly surrounding the graphite filter (counters K, K_1, B, L, L_1), i.e., they fall into the category of showers recorded in the upper part of the apparatus. An example is the case shown in Fig. 2a. Figure 2b gives the integral curves of showers recorded in the upper part of the apparatus in measurements with the graphite filter (1) and without it (2).* Curve 3 is the difference of curves 1 and 2. From Fig. 2b it is seen that there is a considerable background included among the showers in the upper part of the apparatus. This background consists of nonlocal showers, the number of which practically does not change when graphite is placed in the telescope, and of showers from lead with a "backward current" of particles (^{3}). Introducing a correction for the change in showers with a "backward current" of particles when graphite is placed in the telescope, and for the loss of showers from two particles owing to the particles of a shower striking gaps between the counters (see Table 2), gives the true number of interactions in the graphite $N_{\mathrm{int}C}$, represented by curve 4 in Fig. 2b.

With the aid of this method we obtained the following values of the mean free path and cross section for inelastic interaction of protons with carbon nuclei:

$$L_p^C = 76 \pm 7 \text{ g} \cdot \text{cm}^{-2}; \qquad \sigma_p^C = 264 \pm 24 \text{ mb}.$$

We see that the value of the cross section obtained by the method of direct observation of showers from graphite turned out to be 15% smaller than the value obtained by the method of diminution of the flux of single shower-producing particles. It is possible that this difference is explained by the fact that in approximately 10–15% of cases interactions occur without the emission of charged particles of high energy (^{4,5}), which are missed by the apparatus in the direct observation of showers from graphite but are recorded by the first of the methods described. Comparison with the results of cross-section measurements obtained by other authors ($^{6-9}$) also indicates a possible loss of interactions when determining the proton-carbon-nucleus cross section by means of the method of direct observation of showers from graphite.

Conclusions. The cross section for inelastic interaction of protons with an average energy of about 12 BeV with carbon nuclei, measured by us, is equal to 315 ± 50 mb, i.e., within the limits of the measurement errors, it coincides with the geometrical cross section of the carbon nucleus.

V. A. Sobinyakov participated in the work.

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* Corrections for random coincidences and δ-showers have been introduced into the curves. The correction for δ-showers with graphite present in the telescope was $(7.0 \pm 0.2)\%$, and without graphite in the telescope, $(3.0 \pm 0.15)\%$ of the number of recorded single particles. For all points of the curves the root-mean-square statistical error is indicated.

Note: Figure translations are in progress. See original paper for figures.